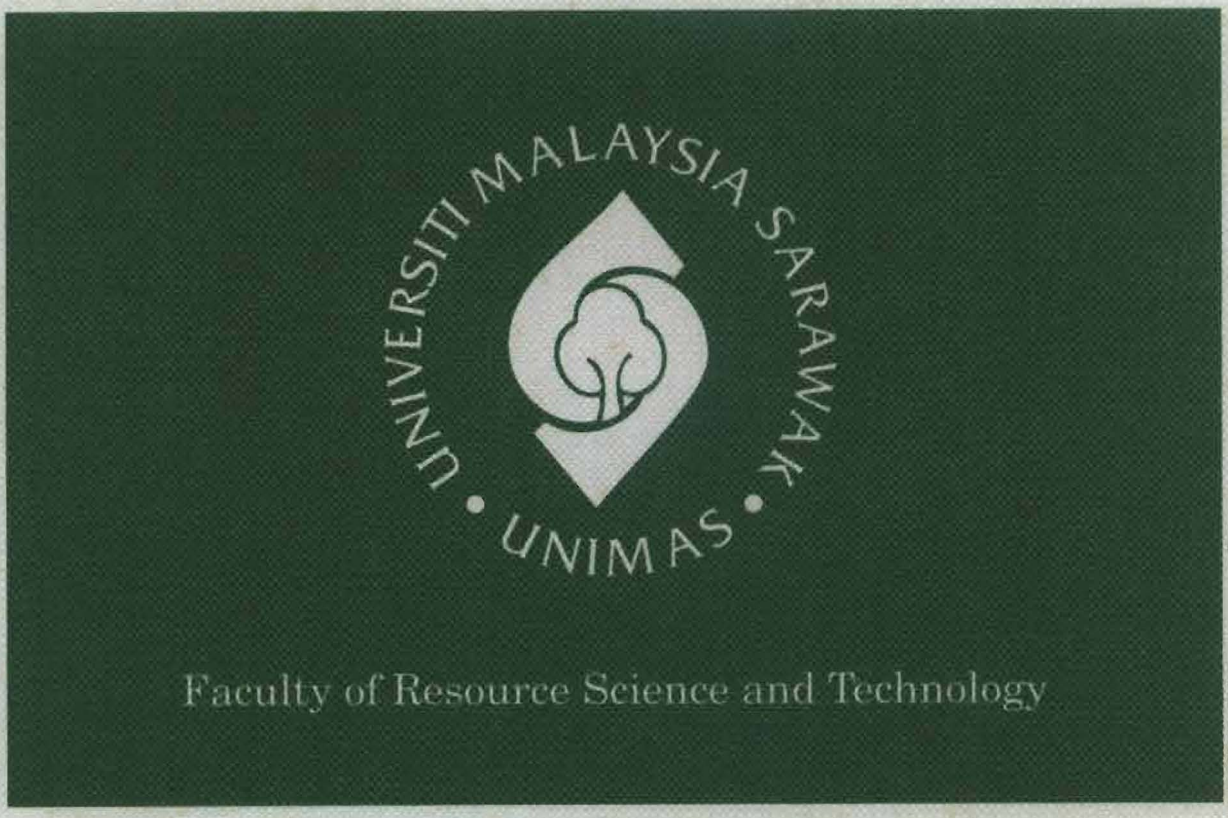


DETERMINATION OF FIBER SATURATION POINT OF SELECTED SARAWAK AND EXOTIC WOOD SPECIES

Low Shook Ling

Bachelor of Science with Honours
(Plant Resource Science and Management)
2009

DETERMINATION OF FIBER SATURATION POINT OF SELECTED SARAWAK AND EXOTIC WOOD SPECIES

LOW SHOOK LING

This project is submitted in partial fulfillment of the requirements for the Degree of Bachelor Science with Honours in Plant Resource Science and Management

Faculty of Resource Science and Technology
Universiti Malaysia Sarawak
2009

APPROVAL SHEET

Name of candidate: Low Shook Ling

Title of Dissertation: Determination of Fiber Saturation Point of Selected Sarawak and Exotic Wood Species

Assoc. Prof. Dr. Andrew Wong Han Hoy

Supervisor

Assoc. Prof. Dr. Ismail Jusoh

Coordinator of Plant Resource Science and Management Programme

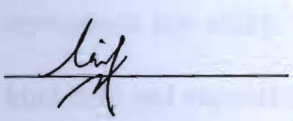
Department of Plant Science and Environmental Ecology

Faculty of Resource Science and Technology

Universiti Malaysia Sarawak

DECLARATION

I declare that no portion of this dissertation has been submitted in support of an application for another degree of qualification of this or any other university or institution of higher learning.



Low Shook Ling
Plant Resource Science and Management
Department of Plant Science and Environmental Ecology
Faculty of Resource Science and Technology
Universiti Malaysia Sarawak

ACKNOWLEDGEMENT

First and foremost, I would like to express my heartfelt gratitude and appreciation to my supervisor, Associate Prof. Dr Andrew Wong Han Hoy for his guidance, advice, assistance and support throughout the completion of this study.

My sincere thanks also goes to Mr. Kandan Jenang and his staff of Timber Research and Technical Training Centre (TRTTC, Kuching) especially Mr. Willies Chin for his help and assistance in the preparation of wood blocks and conducting of portion experiments at TRTTC; Mr. Charles Diyom in his kindness help in wood tissues sliding; and Mr. Yang Min Chin and Mr. Voon Sin Lee for their kindness permission in allowing the use of microscopy equipments.

My special thanks are also candidated to my family members for their encouraging and understanding when i face problem in my work, spiritual, financial and moral support throughout my study in UNIMAS. I earnestly would like to thank my close friends who are far away from me for their constant patience, spiritual support and encouragement throughout my study. My grateful thanks also point to my friends in UNIMAS for their kind help and support throughout the study.

Table of Contents

List of Abbreviations

FSP	Fiber saturation point
MC	Moisture contents
B.density	Basic density
W.permeability	Water permeability
M.extractives	Methanol extractives
C.solubility	Cold water solubility
H.solubility	Hot water solubility
V.density	Vessel density
V.diameter	Vessel diameter
F.length	Fiber length
F.diameter	Fiber diameter
F.L.diameter	Fiber lumen diameter
F.W.thickness	Fiber wall thickness

List of Tables

List of Figures

Determination of Fiber Saturation Point of Selected Sarawak and Exotic Wood Species

Low Shook Ling

Plant Resource Science and Management Programme
Department of Plant Science and Environmental Ecology
Faculty of Resource Science and Technology (FRST)
Universiti Malaysia Sarawak (UNIMAS)

ABSTRACT

Wood is hygroscopic and therefore absorption and desorption occur naturally to achieve an equilibrium of moisture contents between wood and the surrounding environments. In wood, the sorption rate is different for different temperature and was dependent on wood species. Thus, fiber saturation point (FSP) is the key to determine the maximum amount of water that the composite layers of the cell walls can hold at a particular temperature and pressure. The FSP of 10 selected Sarawak wood species and 4 exotic species were determined by Awoyemi (adsorption-desorption intercept) method, Walker method, Awoyemi-Walker method and Vorreiter method. Results showed that the mean FSP of each species was significantly different ($P<0.05$) between the four methods. The FSP by Awoyemi method ranged from 19.83% to 61.25% between species, while the FSP for Walker's method, Awoyemi-walker's and Vorreiter method was range from 9.23% to 32.16%, 9.85% to 35.31% and 20.35% to 41.93% respectively. Analysis with wood physical properties, extractives contents and anatomical properties showed that not all the wood properties correlated significant with FSP. All 4 FSP methods were significantly positively correlated with water permeability ($P<0.05$). Also significantly negative correlation exists between basic density and water permeability, basic density and fiber lumen diameter, solvent extractives and fiber diameter, vessel density and vessel diameter; while positive correlation exists between solvent extractive and cold water solubility, cold water solubility and hot water solubility, fiber length and fiber diameter, fiber length and fiber wall thickness, fiber diameter and fiber lumen diameter ($P<0.05$).

Keywords: Fiber Saturation Point (FSP), Absorption, Desorption, Malaysian timbers, Method

ABSTRAK

Kayu adalah higroskopik, oleh sebab itu, jerapan dan penyejatan kelembapan berlaku secara semulajadi dalam kayu untuk mencapai keseimbangan kelembapan antara kayu dengan keadaan alam sekeliling. Kadar penyerapan dalam kayu adalah berbeza pada suhu tertentu dan bergantung pada jenisan kayu. Oleh demikian, titik ketepuan fiber (fiber saturation point) merupakan kunci utama untuk menentukan jumlah maksimum air yang boleh diserap dan dipegang oleh fiber pada keadaan suhu dan tekanan yang tertentu.10 jenis kayu balak Sarawak dan 4 jenis species eksotik dikaji dengan merujuk kepada kaedah Awoyemi (kaedah pemintasan garis lengkungan penyerapan dan penyejatan), kaedah Walker, Kaedah Awoyemi-Walker, dan kaedah Vorreiter. Keputusan menunjukkan nilai purata titik ketepuan fiber mempunyai perbezaan nyata sekali ($p<0.05$) antara keempat-empat kaedah ini. Titik ketepuan fiber bagi kaedah Awoyemi terletak di antara 19.83% hingga 61.25% antara species kayu, manakala titik ketepuan fiber bagi kaedah Walker, kaedah Awoyemi-Walker dan kaedah Vorreiter masing-masing terletak di antara 9.23% hingga 32.16%, 9.85% hingga 35.31% dan 20.35% hingga 41.93%. Data titik ketepuan fiber bagi empat kaedah ini dikorelasi dengan ciri-ciri fizikal, peratusan kandungan estrak dan ciri-ciri anatomi kayu. Akan tetapi, bukan semua pasangan menunjuk korelasi yang nyata. Keseluruhannya, titik ketepuan fiber dalam empat kaedah ini didapati mempunyai negatif korelasi dengan penyusupan air ($P<0.05$). Didapati juga negative korelasi wujud antara ketumpatan asas kayu dengan penyusupan air, ketumpatan asa kayu dengan diameter fiber lumen, peratusan kandungan ekstrak (methanol) dengan diameter fiber, ketumpatan vessel dengan diameter vessel,; manakala positif korelasi wujud antara peratusan kandungan ekstrak (methanol) dengan peratusan kandungan esktrak (sejuk), kepanjangan fiber dengan diameter fiber, ketebalan fiber dengan ketebalan dinding fiber, diameter fiber dengan diameter fiber lumen ($P<0.05$).

Kata kunci: Titik ketepuan fiber (FSP), Penyerapan, Penyejatan, Kayu balak Malaysia, Kaedah

1.0 Introduction

Absorption and desorption occur naturally in wood to achieve an equilibrium of moisture contents between wood and the surrounding environments. This natural phenomenon not only occurs in fresh wood but also occurs in wood in service. Water or moisture plays an important role in wood where it has significant influences to the physical properties and mechanical properties on wood (Panshin & de Zeeuw, 1980) apart from act as a medium for fluid and chemical transportation in the wood.

The ability of water uptake or permeability into wood and the percentage of moisture contents found in wood differ due to the different structures in wood. In wood, the sorption rate is varies with temperature and was dependent on wood species (Durbak *et al.*, 1998). In addition, Zeronian and Mee (1989) stated that the amount of water absorbed by a cellulosic fiber was influenced by its cellulose crystalline structure and morphology, the ambient relative vapor pressure (RVP), and the direction from which the equilibrium conditioning is approached, i.e. sorption hysteresis. The degree of hysteresis will depend on the temperature and previous conditioning of the sample.

While sorption is a natural phenomenon occurring in wood, it is unknown under which percentage wood moisture content that the rate of absorption and desorption will tend to reach an equilibrium. Thus, fiber saturation point (FSP) becomes the key to determine the maximum amount of water that the composite polymers of the cell wall can hold at a particular temperature and pressure (Awoyemi, 2006) when free water is absent from the cell lumina. Fiber saturation point (FSP) is the point or level at which the cell cavities are fully devoid of free water but the cell walls are fully saturated with bound or adsorbed water (Negi, 1997; Walker, 1993). According to Barkas (1935), the fiber saturation point

of wood is define as the minimum wood moisture content which is in equilibrium with the saturated atmosphere. Through the inter-exchange between adsorption and desorption rate, thus the fiber saturation point is the point of interception between the two sorption curves (Awoyemi, 2006).

Fiber saturation point varies between wood species, some species may achieve fiber saturation point at low moisture content while other species may achieved it at higher moisture content. The fiber saturation point rates will not be the exact value for whole wood log where the water holding capacity may differ at intra-species level, and fluctuate in any part of wood substrate, but an estimate FSP value is obtained for a wood species. Although numerous studies have been done on fiber saturation point determination of timbers in foreign countries using a range of techniques, no studies have been made on Malaysia tropical forest timbers yet. Besides, it is also believed that FSP could be dependent on and correlated with extractive contents, physical and anatomical features of wood possibly affecting absorption-desorption phenomenon.

This research has the following aims:

i) to determine the fiber saturation point of 10 selected Sarawak wood species and 4 exotic species as a screening trial run to gain an appreciation of FSP variations between species and wood substrates,

ii) to compare 4 methods of determining of fiber saturation point (Awoyemi method, Walker method, Awoyemi-Walker method and Vorreiter method), and

iii) to determine the relationships and significance correlation between the fiber saturation point and physical or anatomical features of wood as an attempt to explore wood properties influencing FSP of wood.

2.0 Literature Review

2.1 Moisture absorption and desorption fundamentals

Wood behaves as hydrophilic swelling gel (Barkas, 1932) and is highly hygroscopic (Durbak *et al.*, 1998) whereby it has the ability to take in or give out moisture from its structure. The lignocellulosic material in wood will change in dimensions when the moisture contents change due to the hydroxyl and other oxygen-containing group in the cell wall polymer that attract moisture through hydrogen bonding (Rowell & Rowell, 1989).

The moisture content found in green wood ranges from 60% for hardwoods to about 200% for softwoods (Dinwoodie, 1989). The amounts and rate of moisture adsorbed in wood are fluctuating and depends mainly on the relative humidity and temperature (Durbak *et al.*, 1998) of the surrounding air. However, there are exceptions from such dependency on relative humidity and temperature in species which have high extractive contents such as redwood, cedar and teak (Durbak *et al.*, 1998).

Adsorption occurs within the amorphous cellulosic regions of the cell wall. As woods are soaked in water, intermediately the air spaces fill with water (Panshin & de Zeeuw, 1980). During adsorption, the cell wall swells and the volumetric swelling roughly corresponds to the volume of water adsorbed (Walker, 1993).

If the water vapour pressure in the surrounding atmosphere space is lower than the vapour pressure within wood, desorption will take place (Negi, 1997). When desorption occur, the vapour pressure exert in cell wall and force to fall as water and thus reduces the capillarity. Below the fiber saturation point, the cell wall of wood started to shrink and subsequently

follow by dimensional changes (Walker, 1993). During desorption, complete dispersion (dissolution) in the lumen cell may be prevented due to the strong inter-chain or inter-polymer bonding at certain sites or regions and more energy are needed to break the chain during desorption (Durbak *et al.*, 1998; Panshin & de Zeeuw, 1980). Desorption cease when the vapour pressure within the wood are equal to the vapour pressure in the atmosphere space.

2.2 Fiber saturation point

Water is present in wood in two forms, as free water and bound water. Free water or capillary water is only present in cell lumina and held by capillary forces. Free water is present in green wood at the beginning of the air-seasoning process or when the wood is placed on the process of kiln-drying (Rees & Buckman, 1938). Bound water, also known as hygroscopic water, is present in the cell walls. The bound water is only bound to the matrix constituents of fiber-composite such as lignin, hemicelluloses, and non-crystalline cellulose via hydrogen bond as Van der Waal's forces (Dinwoodie, 1989).

Water in wood moves from higher zones of moisture content gradient to the lower zones of moisture content gradient (Walker *et al.*, 1993). The movement pathway of moisture can be represented as free water, bound liquid and vapor (Rees & Buckman, 1938). As wood dry in oven, the free water will firstly come out from cell lumina and intercellular space while the cell walls are still saturated with bound water (Walker, 1993).

The moisture content at which the cell walls would be saturated while the cell cavities are empty of free water is called the fiber saturation point (FSP) (Hamdan *et al.*, 2007; Durbak *et al.*, 1998; Tiemann, 1906, cited, Siau, 1995). Stone and Scallan (1967) defined fiber

saturation point as the amount of water contained within the water-saturated cell wall. Panshin & de Zeeuw (1980) defined that fiber saturation point refer to the condition when the cell wall is saturated with all the available hydrogen-bonding sites within the cell wall had been occupied by the water molecules. Fiber saturation point is also defined as the moisture content at which free water in cell cavities should be completely removed or devoid, while the cell wall are saturated with bound water or adsorbed water (Negi, 1997; Walker, 1993). According to Barkas (1935), the fiber saturation point of wood is defined as the minimum moisture content which is equilibrium with the saturated atmosphere. Barkas (1935) also state that the fiber saturation point is estimated indirectly from two situations, i.e. the point where shrinkage begins or when the moisture content is reduced from its green state to a point when the compressive strength increases suddenly. Vorreiter (1963, cited, Feist & Tarkow, 1967) defined that the fiber saturation point is a continuously inverse function of bulk density (wood density). This means that the denser the wood, the lower the moisture contents of fiber saturation point for that wood.

The fiber saturation point for most wood species is at a range of 25% - 35% moisture content (**Table 1**), yet some species can have much higher fiber saturation point such as balsa (*Ochroma lagopus*) with FSP of 52% of moisture content (Walker, 1993). A study by Wangaard and Granados (1967) on 9 species of tropical woods show that the actual fiber saturation point of wood was affected by the presence of extractives in situ, and from their research they found that fiber saturation point of these species had increase from the range of 20.5%-32.8% to the range of 30.4%-38.0% after the extractives were remove by a series of neutral solvents, rendering the wood substrate somewhat like sapwood.

Fiber saturation point is important in wood research due to the tremendous effect of water on wood processing and the properties of the material (Awoyemi, 2006). Above the fiber

saturation point, bulking of moisture contents may lead to fungal attacks on wood; while below the fiber saturation point, cracking may happen on wood due to wood shrinkage, although wood strength increases.

At equilibrium moisture content, the wood properties differ according to their sorption state (Arevalo & Hernandez, 2004), and it is clearly influenced by wood density where denser woods were more sensitive to changes in equilibrium moisture content compare to lighter woods (Hernandez, 2007). Under ordinary conditions, the removal of the free water only has little or no effect on wood properties; in contrast there is a pronounced wood property effect on removal of bound water (Durbak *et al.*, 1998). According to Walker (1993), the mechanical properties of wood and the volume of wood will undergo shrinkage when the bound water is remove from the cell walls below fiber saturation point. It is found that the mechanical properties of wood increase almost linearly with decreasing of moisture contents below the fiber saturation point (Walker, 1993). However, the strength of wood may also decrease with decreasing of moisture content because internal stress may occur on to interior of wood owing to desiccation and thus reduce the resistance to the external force since the resistance to external force could depend on variations of bound water content below the fiber saturation point (Noguchi *et al.*, 1965).

2.3 Water permeability

Wood is a porous material which consists of 60 – 70% void volume, but its permeability is quite variable under pressure. The extreme variability in flow of liquid within wood cells is mainly caused by the anisotropic shape and arrangement of the component cells (Durbak *et al.*, 1998). In addition, with 65% of cellulose in wood as crystalline, water cannot gain

access into the crystalline structure but only into the amorphous regions (Stamm, 1964; cited, Wikipedia, 2008).

Permeability was termed as rate of flow of gases and fluids in wood; and it is related to the sizes of the passages that are available for liquids or gases to flow (Panshin & de Zeeuw, 1980). Besides, permeability only can exist under condition of void spaces interconnected by openings; and the fluid transportation through porous solid are influenced by driving forces such as capillary pressure gradient or moisture gradient.

The permeability in hardwoods is very low and weak compare to softwoods, which is due to the complex anatomical structure and higher densities in hardwoods. In hardwoods, permeability in sapwood portion is higher than heartwood portion and it is found in one instance that heartwood is practically zero in the function of permeability (Durbak *et al.*, 1998). Active permeability in sapwood are due to the presence of vessel elements and scalariform perforation plates in hardwood, however presence of tyloses, secreting gums and resins make the vessels in heartwood become retarded in water permeability (Langrish & Walker, 1993) and fluid only can migrate slowly in heartwood portion through diffusion (Keey *et al.*, 2000, cited, Wikipedia, 2008). Presence of tracheids in softwood helps the fluid transport in bulk flow (momentum transfer) (Siau, 1984; cited, Wikipedia, 2008).

The permeability of water is also influenced by the direction of water flow; lateral permeability is very small compared to longitudinal flow (Langrish & Walker, 1993). In longitudinal direction, the permeability is 50 to 100 times greater than in the transverse (radial and tangential) direction (Durbak *et al.*, 1998; Langrish & Walker, 1993). In softwood, bordered pits present in tangential longitudinal direction lead to maximum flow creating an expectation of good correlation between them; while the radial permeability is

found to be poorly correlated with the tangential longitudinal direction but is greater than tangential permeability (Dinwoodie, 1981; Dinwoodie, 1989).

Longitudinal permeability in hardwood is high in the sapwood region. Transverse permeability in hardwood is much lower than in softwood. It is found that good correlation exists between radial and tangential permeability due to the less frequent pitting between adjacent vessels with fibers and low permeability in rays. (Dinwoodie, 1981; Lihra *et al.*, 2000).

It is likely that variations in water permeability in wood substrate between wood species could result in variations in FSP of the wood, although there is lack of evidence for this to date.

2.4 Wood density

The wood density is expressed as the amount of wood substances present per unit volume ($kg\ m^{-3}$) (Dinwoodie, 1989) and it is considered important to wood strength, durability and porosity. Wood density is influenced by the presence of moisture and extractives. As wood absorb water, it induced swelling which increase wood volume and mass (Dinwoodie, 1989). In addition, the dry wood cells may be empty or partly filled with deposits such as gums, resins, or other extraneous substances which make the hardwoods denser than softwoods (Durbak *et al.*, 1998). Thus, the density of softwoods ranges between 350-700 kg/m^3, while hardwoods are 450-1250 kg/m^3 at approximately 12% moisture content and equilibrium to relative humidity of 65% (Desch & Dinwoodie, 1996, cited, Wikipedia, 2008).

Within a species or tree, there is a negative correlation between basic density and moisture content. This mean that the greater the green density of the wood, the lower the basic density; and low basic density lead to high moisture content (Walker, 1993).The density for any wood is designated a mean value due to density variations within the same wood species on account of systematic variation within a single tree, genetic variation and environmental variation between trees of the same species (Dinwoodie, 1989); growth conditions, part of the tree measured, plantation sites, climate, and geographic location (Haygreen & Bowyer, 1996, cited, Jem, 2008). Nevertheless, the density of the actual cell wall material is remarkably constant at about 1500 kg m^{-3} (Dinwoodie, 1989).

The hardness and strength of wood is dependent on the density of wood which in turn is largely determined by the thickness of cell wall and by the proportions of thick-walled and thin-walled cells present in wood (Durbak *et al.*, 1998). As an example, lower density of 176 kg m^{-3} found in balsa (hardwood) may be due to the presence of higher proportion of vessels, and thinner cell walls of the fibers (Dinwoodie, 1989). Denser belian wood is however due to thick fiber walls, high extractive contents and smaller proportion of vessels (Wong & Singh, 1997; Wong & Singh, 2001).

2.5 Vessel, fiber, and fiber membrane

Softwoods only comprise of parenchyma and tracheids. Parenchyma present as small block-like (brick) cells with sizes of 200 x 30 μm are responsible for food material storage, mostly parenchyma are located in the rays. The tracheids are long and pointed fibrous cells with 2 – 4 mm in length (Dinwoodie, 1981). Tracheids are responsible for structural support; and act as conducting pathways in softwoods.

Hardwoods comprised 4 kinds of cells. Besides parenchyma and fiber tracheids, hardwoods also comprise of vessels which act as conduction pathways; and fibers which give structural support to the timbers (Butterfield, 1993). Vessels also known as pores, are short: about 0.2 – 1.2 mm height and relatively wide up to 0.5 mm. Presence of perforation plates at each end of vessels form an efficient conducting tube when 2 or more vessels join end to end. (Dinwoodie, 1981). Fibers are long thin cells similar to thread with very tapered ends and are imperforated. Normally the lengths of fibers are 1 – 2 mm (Dinwoodie, 1981). Inside an actual xylem, all the fibers are strongly bound to each other by the compound middle lamella (Yamamoto *et al.*, 2001).

The thicknesses of each cell are related to the function that the cell will perform. The fiber wall thicknesses are several times greater than that of vessels (Dinwoodie, 1981) due to its major function in structural support. The relative thickness proportions of these cells will also affect the density and other mechanical properties such as strength of wood. In low density woods, the vessels occupy a major proportion of the wood volume, whereas denser woods have a larger proportion of thick-walled fibers (Butterfield, 1993).

Gross anatomical variations between wood species could also influence the wood moisture equilibrium and hence the FSP, although evidence for this is lacking.

2.6 Wood extractives

Wood extractives are the numerous extraneous compounds in wood which can be extracted out using non-polar and polar solvents such as ether, alcohol and water (Uprichard, 1993). In ASTM (2000) method, extractives are defined as those compounds occurring in plant materials but not forming part of the structural elements. Types of compounds that can be

isolated out of wood largely depend upon the polarity of the extraction solvent used (Uprichard, 1993). For example, solvent of ethanol-benzene can extract waxes, fats, some resins, and portion of wood gums. While hot water extractions can extract out tannins, gums, sugars, starches, and coloring matter (ASTM, 2000).

Extractives content in wood may range from 1-20% and varies within and between wood species and the position within tree (Uprichard, 1993; Wong *et al.*, 1983). Miller (1990, cited, Jem, 2008) state that the extractives contents may range from 5-30% with respect to its growth condition, species and time of year the tree is cut. In hardwood, extractives are abundant in the heartwood compared to the sapwood. The extractives contribute in the wood properties such as permeability, specific gravity, hardness, and strength. The colour and odour in wood are also due to the presence of the extractives. In hardwood species, such as tropical species, higher basic densities within the heartwood part are positively correlated with high extractive contents at that part compare to sapwood (Haygreen & Bowyer, 1989b; cited, Ona *et al.*, 1997).

A study by Wangaard and Granados (1967) showed that FSP on 9 species of tropical woods had increased after removing of extractives by a series of neutral solvents in the particular wood. Also, Choong (1969; cited, Ahlgren *et al.*, 1972) found that the FSP had increased after solvent extraction on southern pines. According to Wangaard and Granados (1967), increasing of extractives content reduced equilibrium moisture content due to its bulking effect in cell wall with less hygroscopocity compound materials. Thus, assumption is made that removal of extractives will create pore space in the cell wall which facilitate water permeability (Ahlgren e*t al.*, 1972). However, the study by Ahlgren *et al.*(1972) on both Douglas-fir (*Pseudotsuga menziesii*) and aspen wood (*Populus tremuloides*) showed

that the solvent extraction reduced the FSP compare with water extraction, hence refuting the work of Wangaard and Granodos (1967) or Chong (1969; cited, Alhgren *et al.*, 1972).

Hence, due to the limited evidence of the likely role of wood extractive deposition in situ on FSP, it would be interesting to determine the role between extractive content and FSP accordingly.

3.0 Materials and Methods

3.1 Materials

Sample wood of 13 timber species were collected from sawmills and conditioned. European beech was collected from abroad by A. P. Dr. Andrew Wong. Ten replications of wood blocks were obtained from each species. The wood materials chosen in this study are shown in **Table 2**. These species were coded with simple letters for ease of identification purposes on wood blocks.

Table 2: List of wood species and code

Wood species	Vernacular name	Substrate	Code
Dipterocarpus sp.	Keruing	Heartwood	Ker
Durio sp.	Durian	Sapwood / Heartwood?	D
Endospermum diadenum	Terbulan	Sapwood	Tb
Hydnocarpus sp.	Senumpul	Sapwood	Snp
Lithocarpus sp.	Mempening	Heartwood	MP
Neolamarckia cadamba	Kelampayan	Sapwood	Klpy
Shorea macrophylla	Engkabang Jantong	Sapwood / Heartwood?	E
Shorea sp.	Light Red Meranti	Sapwood / Heartwood?	MRTX
Sindora sp.	Sepetir	Heartwood	Spt
Upuna borneensis	Penyau	Heartwood	P
Acacia mangium	Acacia mangium	Heartwood	AM
Fagus sylvatica	European beech	Sapwood	B
Hevea brasiliensis	Rubberwood	Sapwood	Rb
Tectona grandis	Teak, Jati	Heartwood	T

?= Sapwood or heartwood not clearly differentiated

3.1.1 Study site

The experiments were carried out at the Laboratory of Wood Biodeterioration and Protection Laboratory of Faculty of Resource Science and Technology, Universiti Malaysia Sarawak (UNIMAS). In addition, anatomical studies were also carried out at Timber Research and Technical Training Center (TRTTC).

3.2 Methods

3.2.1 Preparation of wood blocks samples

About ten replicates of wood blocks from fourteen wood species were cut out into the size of 10 mm x 20 mm x 20 (longitudinal) mm. Species codes were written on the surface of each wood block as stated in **Table 2** for identification.

3.2.2 Water permeability determination

In order to test the ability of water uptake for each kind of wood species, initial weight for ten replicates of wood blocks for fourteen wood species respectively were weighed and recorded. The wood blocks were immersed into tap water and immediately vacuum impregnated in water for 15 minutes of treatment. These wood blocks were then re-weighed as final wet weight. The wet wood blocks were then subjected to basic density determination (Section 3.2.3). These wood blocks were finally oven-dried (105^0C) for 48 hours and weighed.

The percentage of water permeability was calculated based on gram of water uptake as:

$$\text{Water permeability} = \frac{\textit{Final weight after vacuum treatment} - \textit{initial weight before soak into water}}{\textit{Oven-dry weight}} \times 100\%$$

3.2.3 Basic density determination

The volume of wood blocks were determined by using "water displacement method" (Wong *et al*, 1983) in where a beaker of tap water was placed on the balance and tared to zero. The wood block which had been used in water permeability determination is hence swollen, and was stucked with a needle and slowly immersed into the water. Reading on the balance was recorded down as the volume of the wood from the mass of water displaced due to immersing the wood blocks into water.

The wood blocks were then dried in oven at 103±2 °C for 48 hours, to zero moisture content. Oven dry weight (g) of the wood blocks was weighed again after drying. The basic density was calculated based on the formula (Walker, 1993) as:

$$\text{Basic density of wood} = \frac{\textit{Oven-dry mass of wood}}{\textit{Swollen volume of wood}}$$

$$\rho = \frac{Kg}{m^3}$$

3.2.4 Oven-dry density determination

Oven-dry volumes of wood blocks were measured by using "water displacement method" of oven dried blocks. Oven dry (105^0C) weight (g) of the wood blocks was based on the oven dry blocks used in the basic density determination (Section 3.2.3). The oven dry density was calculated based on the formula (Walker, 1993) as:

$$\text{Oven dry density of wood} = \frac{\textit{Oven-dry mass of wood}}{\textit{Oven-dry volume of wood}}$$

3.2.5 Fiber saturation point determination

In this study, determination of fiber saturation point was conducted under four different methods which is adsorption-desorption intercept method (Awoyemi method), Walker method, Awoyemi-Walker method and Vorreiter method.

As Table 2 showed the 14 wood species sampled contained either heartwood, sapwood or undifferentiated heartwood zones, it was considered a unique opportunity to compare the FSP of these wood against 4 approaches of determining FSP so that any similarities differences caused by test methods could be detected. Hence using a variety of wood species and wood substrates in this project will also help to screen wood species to gain an idea of general trends in FSP, since there is no previous such studies on Malaysian timber species.

3.2.5.1 Awoyemi method

Awoyemi method was divided into two stages which is adsorption point determination and desorption point determination (Awoyemi, 2006). After all data on absorption and desorption were collected, a sorption-intercept graph (graph of rate of adsorption and desorption at successive intervals versus moisture contents) was plotted by using Microsoft Excel. The rate of absorption and desorption will be measured as change in weight of sorption per hour (g/hr) or the sorption rate as the Y-axis versus the wood moisture content as the X-axis. Fiber saturation point is taken as the point of intersection between absorption and desorption curve or line on the X-Y plots.

3.2.5.1.1 Adsorption point determination

The absorption point was determined by soaking the oven-dry (105^0C) wood blocks immediately in tap water in the beaker. The weight was recorded at interval of 30 minutes. Simultaneously, the percentage of moisture content and rate of adsorption was determined. The study was stopped when the wood moisture content have reach up to or above 35% (occasionally as high as 50% moisture contents).

The percentage wood moisture content during absorption and the rate of absorption were calculated as:

$$\text{Absorption moisture content} = \frac{\textit{Wet weight after absorption} - \textit{oven dry weight}}{\textit{Oven dry weight}} \times 100\%$$

$$\text{Rate of absorption} = \frac{\textit{Block weight gain between a successive time interval}}{\textit{Periodically minutes for absorption at a time interval}} \times 60\text{minutes}$$

$$= \frac{\textit{grammes}}{\textit{hour}}$$

3.2.5.1.2 Desorption point determination

Desorption point determination strictly continuous after absorption point determination. The same wood blocks were evaluated by placed on the laboratory table with surrounding temperature of 23^0C. The weight was recorded in interval of 30 minute. Simultaneously, the percentage of moisture content and rate of desorption was determined. The study will be stopped when the wood moisture content has reach or almost equilibrium with the environment.

The percentage of wood moisture content during desorption and the rate of desorption were calculated as:

Desorption moisture content

= Final absorption moisture contents –

$$\left[\frac{\textit{Final weight for absorption} - \textit{periodical weight for desorption}}{\textit{Final weight for absorption}} \times 100\%\right]$$

$$\text{Rate of desorption} = \frac{\textit{Block weight loss between a successive time interval}}{\textit{Periodically minutes for desorption at a time interval}} \times 60\text{minutes}$$

$$= \frac{\textit{grammes}}{\textit{hour}}$$

3.2.5.2 Walker method

The fiber saturation point determination by the Walker method will be obtained mathematically using the formula of Walker (1993). By inserting the values of volumetric swelling coefficient and basic density found in early experiments into the formula, the moisture contents at fiber saturation point will be derived from the Walker method as shown:

$$\mathbf{V_{Sw}C = MC_{fsp} \times BD \times 10^{-3}}$$

Where:

$V_{Sw}C$ = Volumetric swelling coefficient (%)

$= [(V_{green} - V_{oven})/V_{green}]\ 100\%$

MC_{fsp} = Moisture content at fiber saturation point (%)

BD = Basic density (Kg/m^3)

3.2.5.3 Awoyemi-Walker method

The fiber saturation point determination by the Awoyemi-Walker method will be obtained mathematically using the formula of Walker method modified by Awoyemi (2006), where oven-dry density replaces basic density. By inserting the values of volumetric swelling coefficient and oven-dry density found in early experiments into the formula, the moisture contents at fiber saturation point will be derived for the Awoyemi-Walker method as:

$$\mathbf{V_{Sw}C = MC_{fsp} \times OD \times 10^{-3}}$$

Where:

$V_{Sw}C$ = Volumetric swelling coefficient (%)

$= [(V_{green} - V_{oven})/V_{green}]\ 100\%$

MC_{fsp} = Moisture content at fiber saturation point (%)

OD = Oven-dry density (Kg/m^3)

3.2.5.4 Vorreiter method

In Vorreiter method, the fiber saturation point is established as a continuously decreasing function to the bulk density (Vorreiter, 1963, cited, Feist & Tarkow, 1967). In this method, oven-dry density for each wood sample determined as described in section 3.2.3 was used to read off the fiber saturation point from the enclosed graph (Figure 1) of the inversed relationship between FSP and wood density according to Vorreiter.

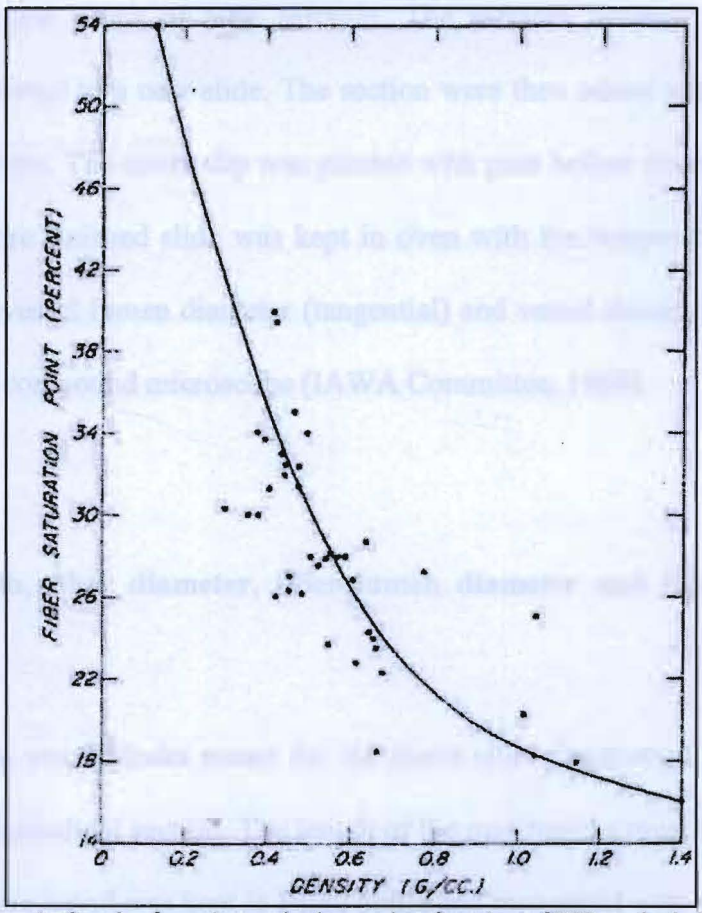


Figure 1: Graph of continuously decreasing function of FSP to the bulk density

3.2.6 Vessel lumen diameter and vessel density determination

To determine the relation between fiber saturation point and vessel lumen diameter and vessel density (number of vessels per mm^2 area), the previous wood sample used in fiber saturation point determination was softened by boiling in water. A small piece of tissue was cut from the wood sample at the cross section (XS) with size 5 mm x 5 mm x 15 µm (thick) using a sliding microtome. The wood tissue was transferred and placed on a slide and stained with few drops of 50% safranin. The safranin residual was cleaned with ethanol and transferred to a new slide. The section were then added with few drops of oil and washed in xylene. The cover slip was painted with gum before covering the section on the slide. The entire finished slide was kept in oven with the temperature of 55^0C for at least 5 days. The vessel lumen diameter (tangential) and vessel density was observed and measured under a compound microscope (IAWA Committee, 1989).

3.2.7 Fiber length, fiber diameter, fiber lumen diameter and fiber wall thickness determination

By using the same wood blocks meant for the above slide preparation, small matchsticks were cut at the longitudinal section. The length of the matchsticks must be in 1 cm or more. The matchsticks size wood was kept in Bijou bottle and macerated with mixture solution of Hydrogen peroxide (H_2O_2) and Acetic acid in the ratio of 1:1. Extra specimens were prepared as reference samples. The entire sample was kept in oven with temperature of 50^0C to 60^0C for four to five days or more than that until the wood had change color to white color. After one week, the reference samples were rinsed several time with distill

water and was shaken to make sure that all the fiber can be fully separated from each other. (IAWA Committee, 1989).

Then fibers were pipetted out from the bottle and put on a clean slide and stained with a few drop of safranin. A cover slip was covered on the slide. Under microscope, the fiber length, fiber diameter, fiber lumen diameter and fiber wall thickness was observed and measured.

3.2.8 Preparation of wood meal

In order to determine the cold water, hot water and methanol soluble materials in wood, the wood blocks were ground into wood meal by using grinder. Wood meal which passes through a 40-mesh screen was used. The wood meal was kept in air tight plastic beg until required for the extractions.

3.2.9 Methanol extraction test

The methanol extractives test is carried out in reference to TAPPI T204 om- 88 with glass extraction thimbles of porosity G2. Two replicates of oven-dry wood meal from each wood species were used for methanol extraction. Each replicate was weighted to at least 4 grammes into glass thimble. The round bottom flask was cleaned, dried and filled with 150 ml of methanol. The extraction thimble filled with wood meals was placed in position in the soxhlet apparatus. The round bottom flask then was connected to the extraction apparatus and water flow generated to the condenser section. The heater was adjusted to provide a boiling rate which will cycle the solvent at least 6 times per hour. The extraction

was carried on at a 6 hours period. The thimbles of extracted wood meals were removed and oven dried for more than 2 hours at 105±3^{0}C. Then the thimbles bearing extracted wood meal were cooled in desiccators for 20 minutes and weighed to the nearest 0.1 mg (TAPPI, 1988).

The extractive content was calculated as:

Extractables, % =

$$\frac{\text{oven-dry weight of unextracted wood meal} - \text{oven-dry weight of extracted wood meal}}{\text{oven-dry weight of unextracted wood meal}} \times 100$$

3.2.10 Cold water solubility test

Water solubility test was carried out in reference to ASTM D1110–84 and TAPPI T207 om-88, with modifications for the determination of the cold water soluble materials in wood. Two replicates of oven-dry wood meal from each wood species were used for cold water extraction. Each replicate was weighted to at least 2 grammes into a 400 ml plastic bottle. Distilled water was added slowly up to 300ml. The cold water extraction was carried out at 23±2^{0}C with constant stirring for 48 hours. The extracted wood meal was transferred to a glass thimble (porosity G2) to filter out the extraneous materials. The extracted wood meals were then oven-dried for 12 hour at 105±3^{0}C and then cooled in desiccators for 20 minutes and weighed to the nearest 0.1 mg (TAPPI, 1988; ASTM, 2000).

The cold water solubility was calculated as:

Cold water solubility, % =

$$\frac{\text{oven-dry weight of unextracted wood meal} - \text{oven-dry weight of extracted wood meal}}{\text{oven-dry weight of unextracted wood meal}} \times 100$$

3.2.11 Hot water solubility test

Two replicates of oven-dry wood meal from each wood species were used for hot water extraction. Each replicate was weighted to at least 2 grammes into a 400 ml conical flask. Distilled water was added slowly up to 300ml. The hot water extraction was autoclaved twice at 120^0C for 15 minutes each time. The extracted wood meal was transferred to glass thimble (porosity G2) to filter out the extraneous materials. The extracted wood meals were then oven-dried for 12 hour at 105 ± 3^0C and then cooled in desiccators for 20 minutes and weighed to the nearest 0.1 mg.

The hot water solubility was calculated as:

Hot water solubility, % =

$$\frac{\textit{oven-dry weight of unextracted wood meal} - \textit{oven-dry weight of extracted wood meal}}{\textit{oven-dry weight of unextracted wood meal}} \times 100$$

3.3 Statistical analysis

The data collected were analyzed by using SPSS software version 15.0. Apart from that, charts and descriptive statistics will be prepared by using Microsoft Excel. Data was integrated using one-way ANOVA, to test the significance of the parameters percentage of water permeability, wood basic density, methanol extractives content, cold water solubility, hot water solubility, vessel density, vessel lumen diameter, fiber length, fiber lumen diameter and fiber wall thickness. All mean values were compared by Duncan's multiple range test at 5% significance level.

Fiber saturation point variations between 14 species of wood blocks and four different methods was analyzed by two-way ANOVA. All mean values were compared by Least Significance Difference (LSD) at 5% significance level for multiple comparisons of mean values. The LSD value was evaluated using the Mean Square Errors from two- way ANOVA tables. Below was the LSD formula:

$$LSD = \sqrt{\frac{2\times MSE}{n}} \quad X \; t_{df\ error}(0.025)$$

n= replicates

MSE= Mean Square Errors

(t_v) (0.025)= based on degrees of freedom

Correlation analysis between the 4 methods of fiber saturation point with all the physical properties, chemical analysis and anatomy properties were tested at 5% significance level. Correlations among the 4 methods of FSP determination were also made to examine the reliability of the FSP results among these methods, via evidence of strong relationships between any two FSP methods.

Table 4: Mean value for percentage of water permeability (%) of 14 wood species

Species	Mean water permeability (%)
Dipterocarpus sp. (Keruing)	40.60 *abc* (1.33)
Durio sp. (Durian)	71.61 *d* (6.58)
Endospermum diadenum (Terbulan)	179.29 *g* (21.39)
Hydnocarpus sp. (Senumpul)	57.69 *cd* (1.55)
Lithocarpus sp. (Mempening)	45.05 *bc* (14.95)
Neolarmarkia cadamba (Kelampayan)	130.69 *f* (30.85)
Shorea macrophylla (Engkabang jantong)	95.66 *e* (18.12)
Shorea sp. (Light Red Meranti)	181.60 *g* (44.71)
Sindora sp. (Sepetir)	100.36 *e* (8.28)
Upuna borneensis (Penyau)	24.71 *a* (9.08)
Acacia mangium (Acacia mangium)	29.70 *ab* (3.30)
Fagus sylvatica (European beech)	95.28 *e* (3.96)
Hevea brasiliensis (Rubberwood)	93.60 *e* (20.93)
Tectona grandis (Teak)	26.22 *a* (10.72)

The mean value sharing the same italized letter does not differ significantly (at 5% level)
Standard deviation value for each mean is shown in parentheses
Mean value (replication,n= 10) compared using Duncan's multiple range test

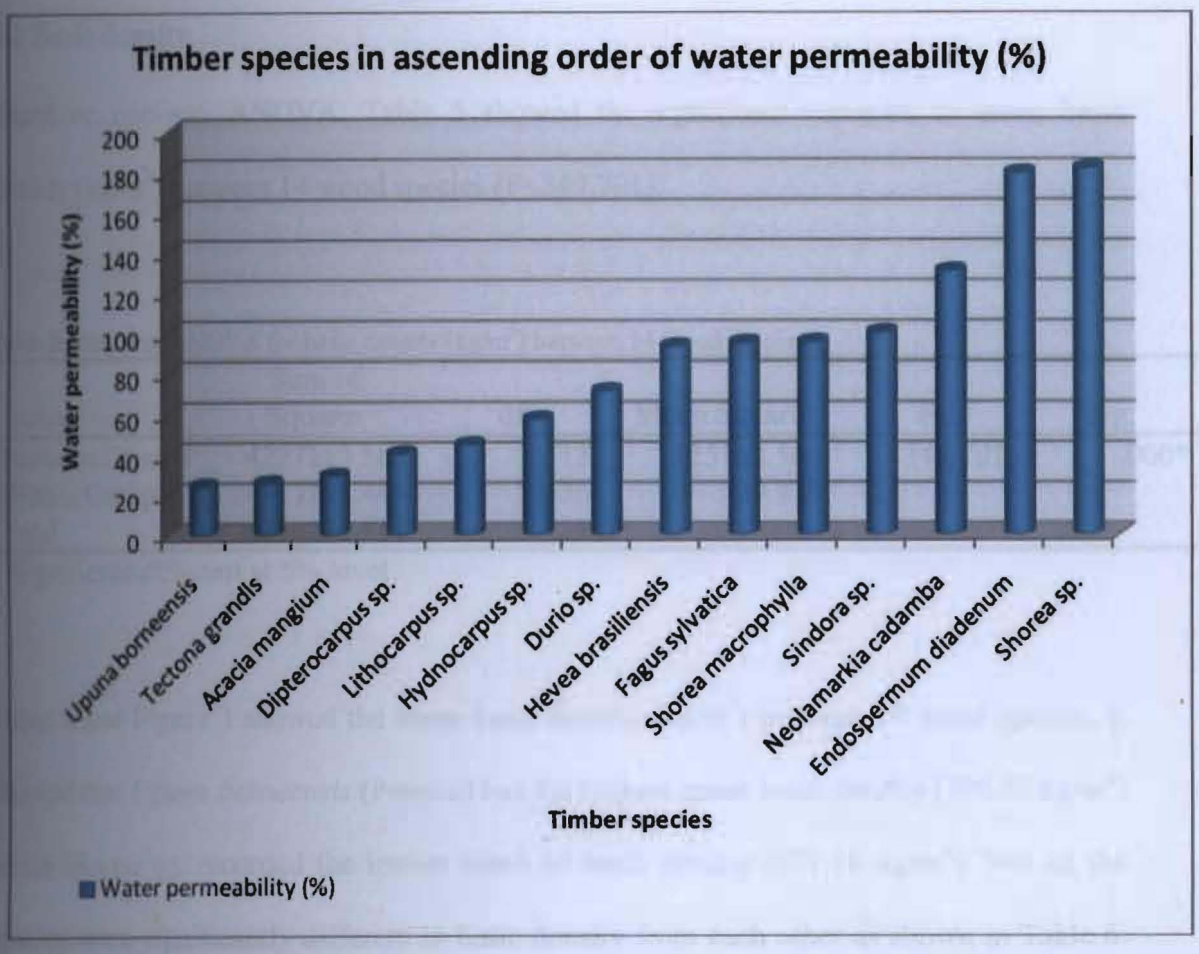


Figure 2: Percentage of water permeability (%) of 14 timber species in ascending order

4.2 Basic density

Based on one-way ANOVA, Table 5 showed the significant variation in mean basic density (kg/m^3) between 14 wood species (F=349.701).

Table 5: One- way ANOVA for basic density (kg/m^3) between 14 wood species

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	4227113.363	13	325162.566	349.701	.000*
Within Groups	117158.448	126	929.829		
Total	4344271.811	139			

* Significant different at 5% level

Table 6 and Figure 3 showed the mean basic density (kg/m^3) between 14 wood species, It showed that *Upuna borneensis* (Penyau) has the highest mean basic density (795.53 kg/m^3) while *Shorea* sp. recorded the lowest mean of basic density (271.18 kg/m^3). Not all the species were significantly different in basic density from each other as shown in Table 6. For example the basic density of *Sindora* sp. (Sepetir), *Fagus sylvatica* (European beech) and *Hevea brasiliensis* (Rubberwood) were quite similar statistically (542.464 kg/ m^3 – 562.479 kg/m^3), while for another group comprising *Neolarmarkia cadamba* (Kelampayan) and *Shorea* sp. (Light Red Meranti) were also quite similar (P<0.05).

Table 6: Mean value of basic density (kg/m^3) between 14 wood species

Species	Mean basic density (kg/m^3)
Dipterocarpus sp. (Keruing)	747.158 *h* (4.040)
Durio sp. (Durian)	660.956 *f* (29.724)
Endospermum diadenum (Terbulan)	373.716 *c* (32.943)
Hydnocarpus sp. (Senumpul)	708.148 *g* (11.236)
Lithocarpus sp. (Mempening)	713.623 *g* (28.542)
Neolarmarkia cadamba (Kelampayan)	276.959 *a* (4.008)
Shorea macrophylla (Engkabang jantong)	309.131 *b* (27.472)
Shorea sp. (Light Red Meranti)	271.178 *a* (11.808)
Sindora sp. (Sepetir)	542.464 *d* (29.860)
Upuna borneensis (Penyau)	795.529 *i* (48.251)
Acacia mangium (Acacia mangium)	659.312 *f* (28.244)
Fagus sylvatica (European beech)	544.893 *d* (7.300)
Hevea brasiliensis (Rubberwood)	562.479 *d* (59.419)
Tectona grandis (Teak)	630.935 *e* (39.750)

The mean value sharing the same italized letter does not differ significantly (at 5% level)
Standard deviation value for each mean is shown in parentheses
Mean value (replication,n= 10) compared using Duncan's multiple range test

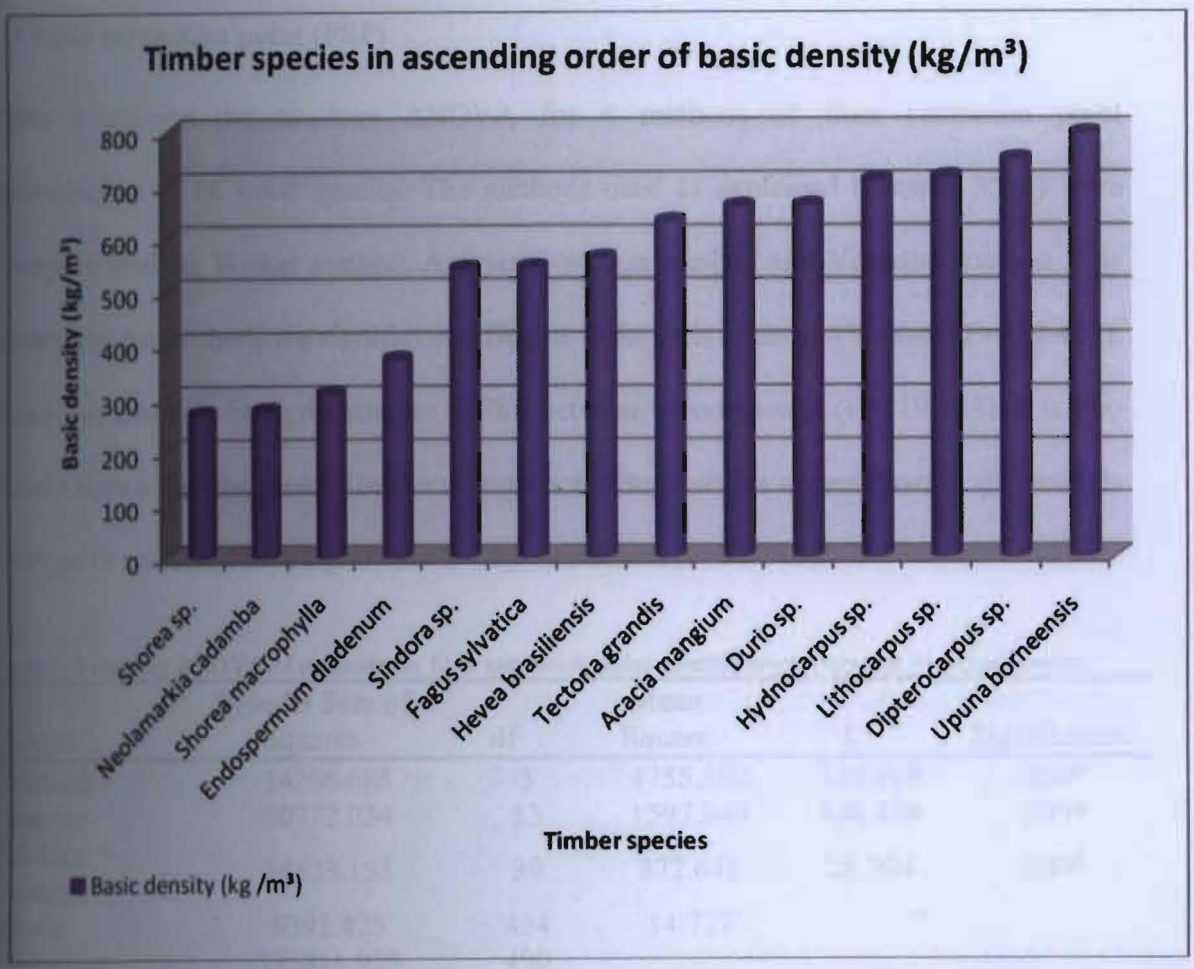


Figure 3: Comparison of basic density (kg/m³) of 14 timber species in ascending order

4.3 Fiber saturation point (FSP)

Table 7 showed the two-way ANOVA for 4 methods of fiber saturation point determination of 14 wood species. The methods used as explained (Section 3.2.5) were Awoyemi method, Walker method, Awoyemi-Walker method and Vorreiter method. It is shown that the methods are significant different from each other at 5% level (F=439.443). There was also significant differences in FSP between wood species (F=119.188). It is also clearly shown that the mean fiber saturation point depends on a combination of methods and type of species, due to significant 2-way interaction (F=33.513).

Table 7: Two- way ANOVA of methods for fiber saturation point determination between 14 wood species

Source	Type III Sum of Squares	df	Mean Square	F	Significance
Method	14266.685	3	4755.562	322.919	.000*
Species	20772.034	13	1597.849	108.499	.000*
Method * Species	14533.155	39	372.645	25.304	.000*
Error	6391.425	434	14.727		
Total	373811.933	490			
Corrected Total	55932.069	489			

a R Squared = .886 (Adjusted R Squared = .871)

4.3.1 FSP by the Awoyemi method

Table 8 showed the mean percentage (%) fiber saturation point wood moisture content between 14 wood species based on the Awoyemi method. Among species, the highest mean fiber saturation point was *Endospermum diadenum* (Terbulan) with the value of 61.25% while *Upuna borneensis* (Penyau) gave the lowest mean fiber saturation point of 19.83%. Some of the mean fiber saturation point were significantly different ($P<0.05$) between species. For example, FSP of *Dipterocarpus* sp. (Keruing), *Upuna borneensis* (Penyau), *Acacia mangium*, *Durio* sp. (Durian), *Hydnocarpus* sp. (Senumpul) and *Lithocarpus* sp. (Mempening) were quite similar statistically (19.83% - 28.49%), while another group comprising of *Fagus sylvatica* (European beech), *Shorea macrophylla* (Engkabang jantong), and *Sindora* sp. (Sepetir) were also quite similar ($P<0.05$).

Table 8: Mean percentage (%) FSP of 14 species by the Awoyemi method

Method	Species	Mean FSP (%)
Awoyemi method	*Dipterocarpus* sp. (Keruing)	21.90 *ab* (0.76)
	Upuna borneensis (Penyau)	19.83 *a* (1.20)
	Acacia mangium (Acacia mangium)	28.38 *abcd* (4.41)
	Fagus sylvatica (European beech)	48.00 *ef* (4.61)
	Hevea brasiliensis (Rubberwood)	54.28 *fg* (11.33)
	Tectona grandis (Teak)	29.38 *bcd* (3.85)
	Durio sp. (Durian)	28.49 *abcd* (1.91)
	Endospermum diadenum (Terbulan)	61.25 *g* (11.81)
	Hydnocarpus sp. (Senumpul)	27.29 *abc* (2.38)
	Lithocarpus sp. (Mempening)	24.68 *abc* (2.94)
	Neolarmarkia cadamba (Kelampayan)	36.86 *d* (7.00)
	Shorea macrophylla (Engkabang jantong)	50.89 *ef* (4.82)
	Shorea sp. (Light Red Meranti)	33.31 *cd* (9.03)
	Sindora sp. (Sepetir)	45.20 *e* (7.84)

The mean value sharing the same italized letter does not differ significantly (at 5% level)
Standard deviation value for each mean is shown in parentheses
Mean value (replication, n= 5) compared using Duncan's multiple range test

An example of the Awoyemi graphical adsorption-desorption intercept method is shown in Figure 4 for *Acacia mangium* where the intercept estimated the FSP to be at 28.28% wood moisture content.

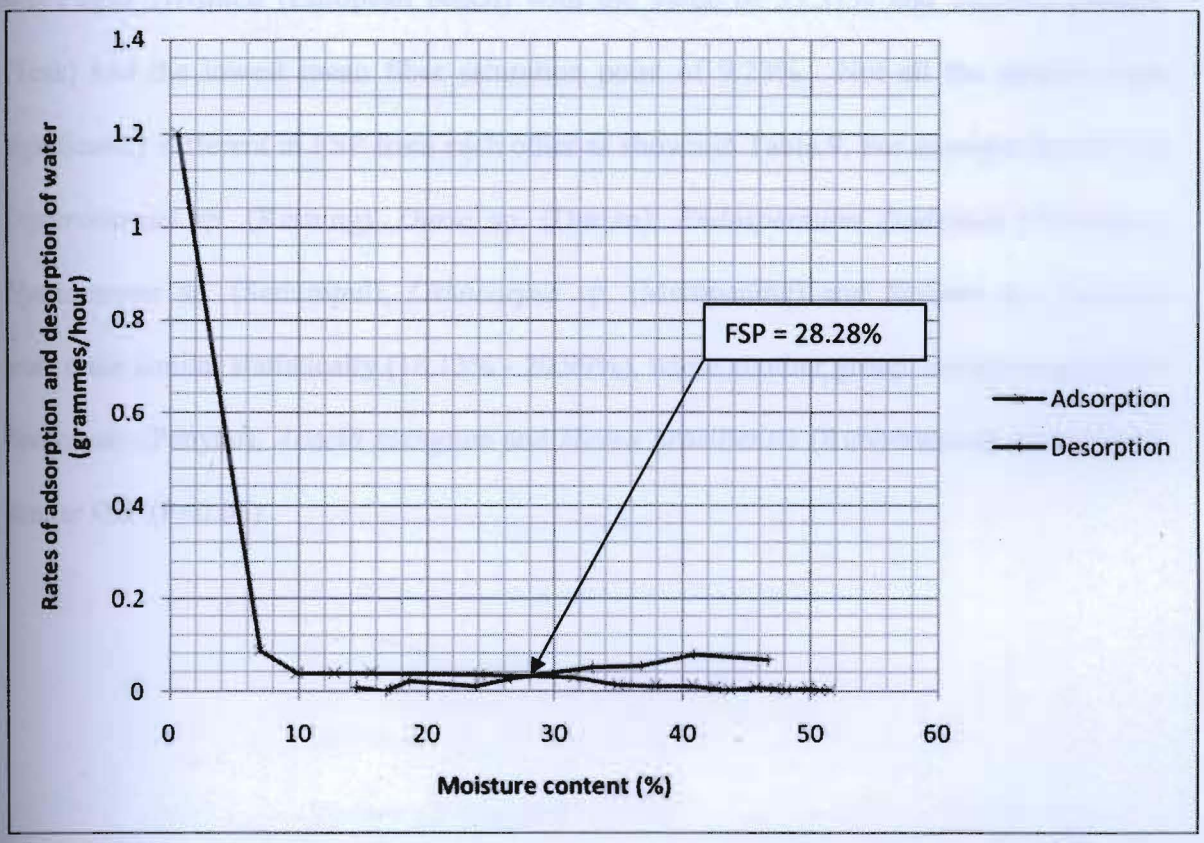


Figure 4: Trend of adsorption and desorption curve in *Acacia mangium* and its' moisture content at FSP

4.3.2 FSP by the Walker method

Table 9 showed the mean percentage (%) fiber saturation point between 14 wood species based on the Walker method. Among these species, the highest mean fiber saturation point was *Fagus sylvatica* (European beech) with the value of 33.51% and *Tectona grandis* (Teak) had the lowest mean fiber saturation point of 9.23%. Not all the species were significantly different in FSP from each other as shown in Table 9. For example the FSP of *Dipterocarpus* sp. (Keruing), *Durio* sp. (Durian), *Endospermum diadenum* (Terbulan), *Hydnocarpus* sp. (Senumpul), *Lithocarpus* sp. (Mempening) and *Sindora* sp. (Sepetir) were quite similar statistically (18.13% - 20.99%), while another group, comprising *Upuna borneensis* (Penyau), *Acacia mangium* and *Hevea brasiliensis* (Rubberwood) shared quite similar FSP ($P<0.05$).

Table 9: Mean percentage (%) fiber saturation point of 14 species by the Walker method

Method	Species	Mean FSP (%)
Walker method	*Dipterocarpus* sp. (Keruing)	20.41 *de* (0.68)
	Upuna borneensis (Penyau)	12.51 *b* (4.68)
	Acacia mangium (Acacia mangium)	13.87 *b* (5.71)
	Fagus sylvatica (European beech)	33.51 *g* (3.20)
	Hevea brasiliensis (Rubberwood)	15.66 *bc* (1.70)
	Tectona grandis (Teak)	9.23 *a* (2.47)
	Durio sp. (Durian)	20.99 *de* (1.36)
	Endospermum diadenum (Terbulan)	20.30 *de* (2.57)
	Hydnocarpus sp. (Senumpul)	19.06 *de* (5.20)
	Lithocarpus sp. (Mempening)	18.13 *cd* (1.84)
	Neolarmarkia cadamba (Kelampayan)	25.39 *f* (4.42)
	Shorea macrophylla (Engkabang jantong)	22.02 *e* (2.70)
	Shorea sp. (Light Red Meranti)	32.16 *g* (5.73)
	Sindora sp. (Sepetir)	18.96 *de* (1.59)

The mean value sharing the same italized letter does not differ significantly (at 5% level)
Standard deviation value for each mean is shown in parentheses
Mean value (replication, n= 10) compared using Duncan's multiple range test

4.3.3 FSP by the Awoyemi-Walker method

Table 10 showed the mean percentage (%) of fiber saturation point between 14 wood species based on Awoyemi-Walker method. Among species, the highest mean fiber saturation point was *Fagus sylvatica* (European beech) with the value of 41.09% and *Tectona grandis* (Teak) had the lowest mean fiber saturation point of 9.85%. Not all the species were significantly different in FSP from each other as shown in Table 10. For example the FSP of *Dipterocarpus* sp. (Keruing), *Durio* sp. (Durian), *Endospermum diadenum* (Terbulan), *Hydnocarpus* sp. (Senumpul), *Lithocarpus* sp. (Mempening), *Shorea macrophylla* (Engkabang jantong) and *Sindora* sp. (Sepetir) shared similar values statistically (20.85% - 24.39%), while another group comprising *Upuna borneensis* (Penyau), *Acacia mangium* and *Hevea brasiliensis* (Rubberwood) also shared quite similar FSP ($P<0.05$).

Table 10: Mean percentage (%) fiber saturation point of 14 species by the Awoyemi-Walker method

Method	Species	Mean FSP (%)
Awoyemi-Walker method	*Dipterocarpus* sp. (Keruing)	24.08 *de* (0.93)
	Upuna borneensis (Penyau)	14.06 *b* (5.46)
	Acacia mangium (Acacia mangium)	15.51 *b* (7.24)
	Fagus sylvatica (European beech)	41.09 *g* (4.71)
	Hevea brasiliensis (Rubberwood)	17.18 *bc* (1.96)
	Tectona grandis (Teak)	9.85 *a* (2.82)
	Durio sp. (Durian)	24.39 *de* (1.86)
	Endospermum diadenum (Terbulan)	21.97 *d* (2.93)
	Hydnocarpus sp. (Senumpul)	22.29 *d* (6.58)
	Lithocarpus sp. (Mempening)	20.85 *cd* (2.34)
	Neolarmarkia cadamba (Kelampayan)	27.38 *e* (5.19)
	Shorea macrophylla (Engkabang jantong)	23.62 *de* (2.97)
	Shorea sp. (Light Red Meranti)	35.31 *f* (6.79)
	Sindora sp. (Sepetir)	21.14 *cd* (1.94)

The mean value sharing the same italized letter does not differ significantly (at 5% level)
Standard deviation value for each mean is shown in parentheses
Mean value (replication, n= 10) compared using Duncan multiple range test

4.3.4 FSP by the Vorreiter method

Table 11 showed the mean percentage (%) fiber saturation point between 14 wood species by the Vorreiter method. Among species, the highest mean fiber saturation point was *Neolarmarkia cadamba* (Kelampayan) with the value of 43.32% and *Upuna borneensis* (Penyau) provided the lowest mean fiber saturation point of 20.23%. Some of the species were significantly different ($P<0.05$) in FSP. For example the FSP of *Dipterocarpus* sp. (Keruing), *Upuna borneensis* (Penyau), *Hydnocarpus* sp. (Senumpul) and *Lithocarpus* sp. (Mempening) were quite similar statistically (20.23% - 21.23%), while another group comprising *Hevea brasiliensis* (Rubberwood) and *Sindora* sp. (Sepetir) were also quite similar ($P<0.05$).

Table 11: Mean percentage (%) fiber saturation point of 14 species by the Vorreiter method

Method	Species	Mean FSP (%)
Vorreiter method	*Dipterocarpus* sp. (Keruing)	20.35 *a* (0.10)
	Upuna borneensis (Penyau)	20.23 *a* (0.59)
	Acacia mangium (Acacia mangium)	23.10 *c* (0.78)
	Fagus sylvatica (European beech)	24.62 *d* (0.60)
	Hevea brasiliensis (Rubberwood)	26.55 *e* (2.34)
	Tectona grandis (Teak)	24.55 *d* (1.38)
	Durio sp. (Durian)	22.15 *bc* ((0.92)
	Endospermum diadenum (Terbulan)	35.98 *f* (2.05)
	Hydnocarpus sp. (Senumpul)	21.02 *ab* (0.62)
	Lithocarpus sp. (Mempening)	21.23 *ab* (0.67)
	Neolarmarkia cadamba (Kelampayan)	43.32 *i* (0.62)
	Shorea macrophylla (Engkabang jantong)	40.64 *g* (2.39)
	Shorea sp. (Light Red Meranti)	41.93 *h* (1.07)
	Sindora sp. (Sepetir)	26.59 *e* (1.21)

The mean value sharing the same italized letter does not differ significantly (at 5% level)
Standard deviation value for each mean is shown in parentheses
Mean value (replication, n= 10) compared using Duncan's multiple range test

Figure 5 shows the determination of FSP for 10 block replicates of *Shorea macrophylla* (Engkabang jantong) based on graphical Vorreiter method.

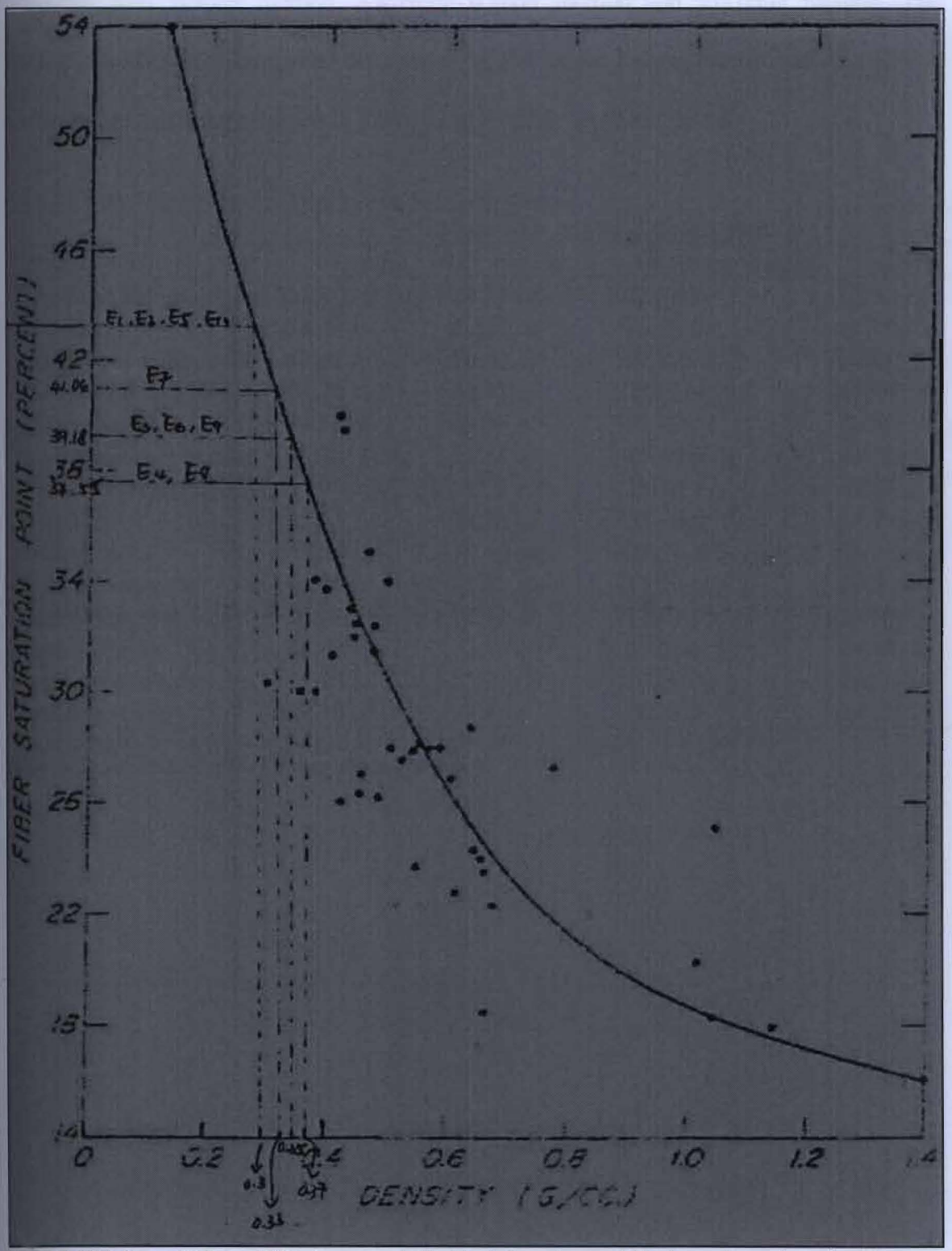


Figure 5: FSP determination of *Shorea macrophylla* (Engkabang jantong) block specimens by using the graphical Vorreiter method

Table 12, Figure 6 and Figure 7 showed the overall FSP pooling 4 methods and 14 wood species. Clearly the Awoyemi method gives highly erratic FSP values for most species compared with Walker method, Awoyemi-Walker method and Vorreiter method. The relative statistical similarities of differences in FSP among the combinations of methods and wood species is highlighted in Table 12 at $P<0.05$ significant level.

Table 12: Mean FSP between 14 timber species and test methods

	Mean FSP (%) by different method			
Species	Awoyemi	Walker	Awoyemi-Walker	Vorreiter
Dipterocarpus sp.	21.90 *cd*	20.34 *cd*	23.98 *de*	20.40 *cd*
Durio sp.	28.49 *e*	20.63 *cd*	23.88 *de*	22.35 *cd*
Endospermum diadenum	61.25 *j*	20.40 *cd*	21.99 *cd*	37.23 *fg*
Hydnocarpus sp.	27.29 *de*	20.81 *cd*	24.51 *de*	20.73 *cd*
Lithocarpus sp.	24.68 *de*	18.59 *c*	21.42 *cd*	21.27 *cd*
Neolarmarkia cadamba	36.86 *fg*	23.67 *de*	25.36 *de*	43.23 *gh*
Shorea macrophylla	50.89 *i*	21.78 *cd*	23.38 *d*	40.03 *g*
Shorea sp.	33.31 *f*	32.21 *ef*	35.38 *fg*	41.95 *gh*
Sindora sp.	45.20 *h*	19.10 *cd*	21.30 *cd*	26.68 *de*
Upuna borneensis	19.83 *cd*	12.52 *ab*	13.99 *bc*	20.26 *cd*
Acacia mangium	28.38 *e*	12.42 *ab*	13.61 *b*	23.06 *cd*
Fagus sylvatica	48.00 *hi*	32.14 *ef*	39.06 *g*	24.89 *de*
Hevea brasiliensis	54.28 *i*	15.95 *bc*	17.50 *bc*	26.75 *de*
Tectona grandis	29.38 *ef*	7.87 *a*	8.28 *a*	24.85 *de*

The mean value sharing the same italized letter does not differ significantly (at 5% level)
Mean value (replication, n= 5) compared using LSD=4.77

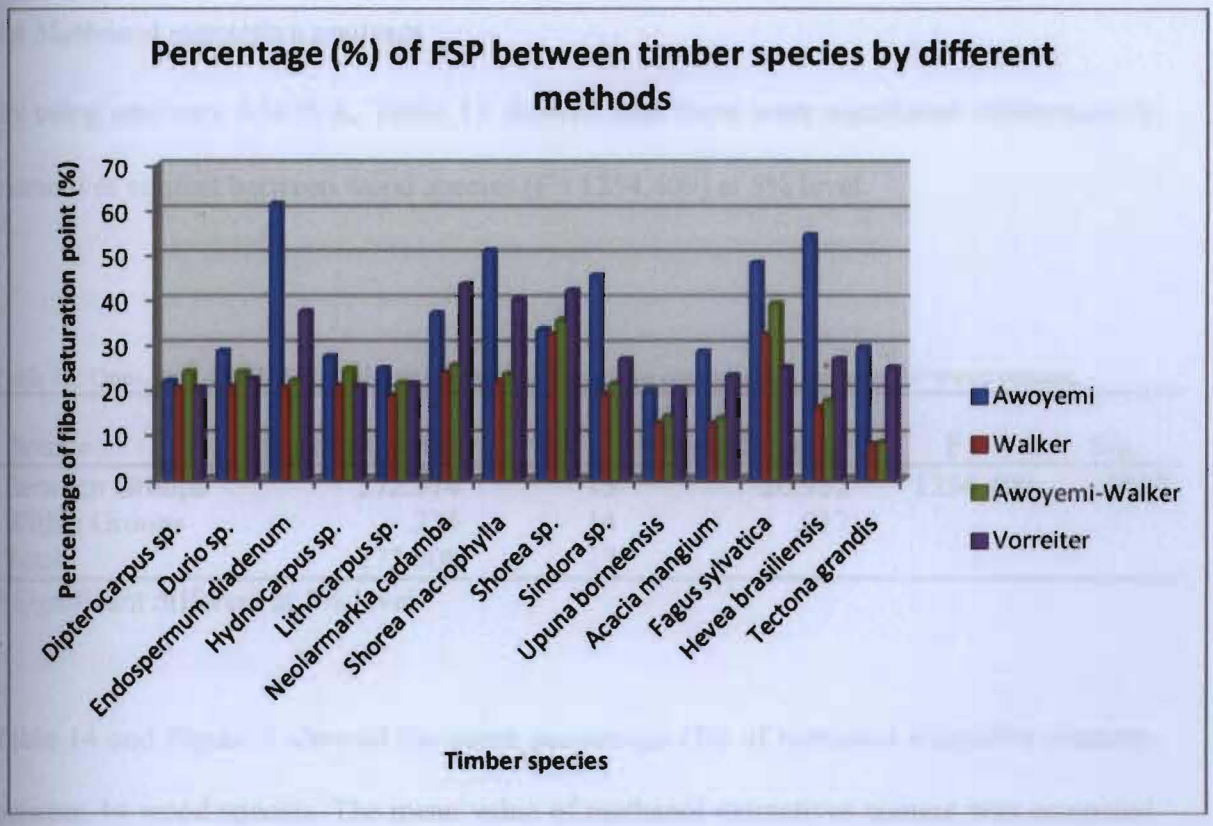


Figure 6: Comparison of FSP (%) between 14 timber species regarding to different methods

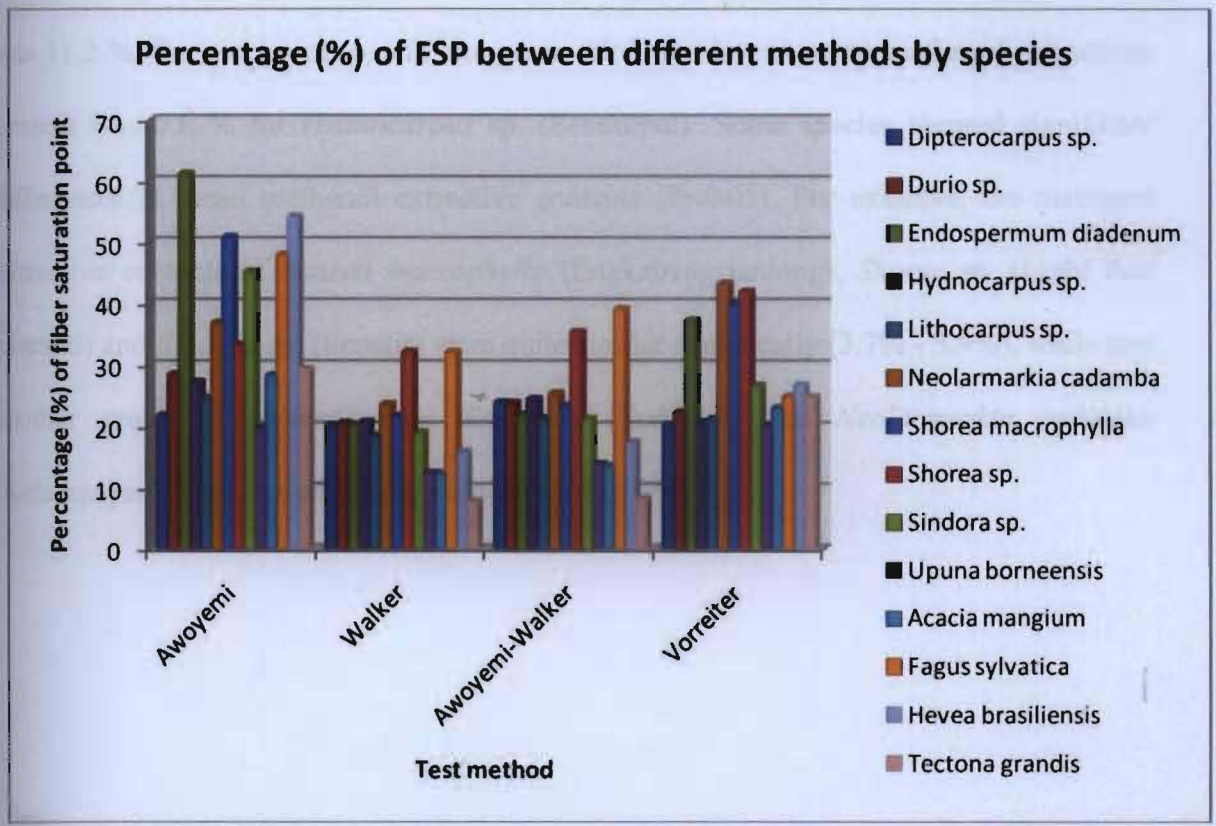


Figure 7: Comparison of FSP (%) between 4 methods regarding to 14 timber species

4.4 Methanol extractive contents

By using one-way ANOVA, Table 13 showed that there were significant differences in extractives content between wood species (F= 1254.409) at 5% level.

Table 13: One- way ANOVA for solvent (methanol) extractive contents (%) between 14 wood species

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	272.374	13	20.952	1254.409	.000*
Within Groups	.234	14	.017		
Total	272.608	27			

* Significant different at 5% level

Table 14 and Figure 8 showed the mean percentage (%) of methanol extractive contents between 14 wood species. The mean value of methanol extractives content was compared by using Duncan's multiple range test. The highest mean percentage of extractives content was 11.2 %, for species of *Acacia mangium*, while the lowest mean methanol extractives content was 0.8 % for *Hydnocarpus* sp. (Senumpul). Some species showed significant differences in mean methanol extractive contents ($P<0.05$). For example, the methanol extractive contents of *Shorea macrophylla* (Engkabang jantong), *Shorea* sp. (Light Red Meranti) and *Sindora* sp. (Sepetir) were quite similar statistically (3.7% - 3.9%), while that another group of *Endospermum diadenum* (Terbulan) and *Neolarmarkia cadamba* (Kelampayan) were shared similar value statically ($P<0.05$).

Table 14: Mean percentage (%) methanol extractive contents between 14 wood species

Species	Substrate	Mean methanol extractive contents (%)
Dipterocarpus sp. (Keruing)	Heartwood	5.4 *h* (0.3)
Durio sp. (Durian)	Sapwood / Heartwood?	1.2 *b* (0.02)
Endospermum diadenum (Terbulan)	Sapwood	2.5 *d* (0.2)
Hydnocarpus sp. (Senumpul)	Sapwood	0.8 *a* (0.01)
Lithocarpus sp. (Mempening)	Heartwood	4.5 *g* (0.1)
Neolarmarkia cadamba (Kelampayan)	Sapwood	2.3 *d* (0.1)
Shorea macrophylla (Engkabang jantong)	Sapwood / Heartwood?	3.9 *f* (0.03)
Shorea sp. (Light Red Meranti)	Sapwood / Heartwood?	3.8 *f* (0.1)
Sindora sp. (Sepetir)	Heartwood	3.7 *f* (0.1)
Upuna borneensis (Penyau)	Heartwood	9.9 *j* (0.1)
Acacia mangium (Acacia mangium)	Heartwood	11.2 *k* (0.2)
Fagus sylvatica (European beech)	Sapwood	1.5 *c* (0.02)
Hevea brasiliensis (Rubberwood)	Sapwood	3.3 *e* (0.04)
Tectona grandis (Teak)	Heartwood	8.4 *i* (0.1)

?= Sapwood or heartwood not clearly differentiated
The mean value sharing the same italized letter does not differ significantly (at 5% level)
Standard deviation value for each mean is shown in parentheses
Mean value (replication, n= 2) compared using Duncan's multiple range test

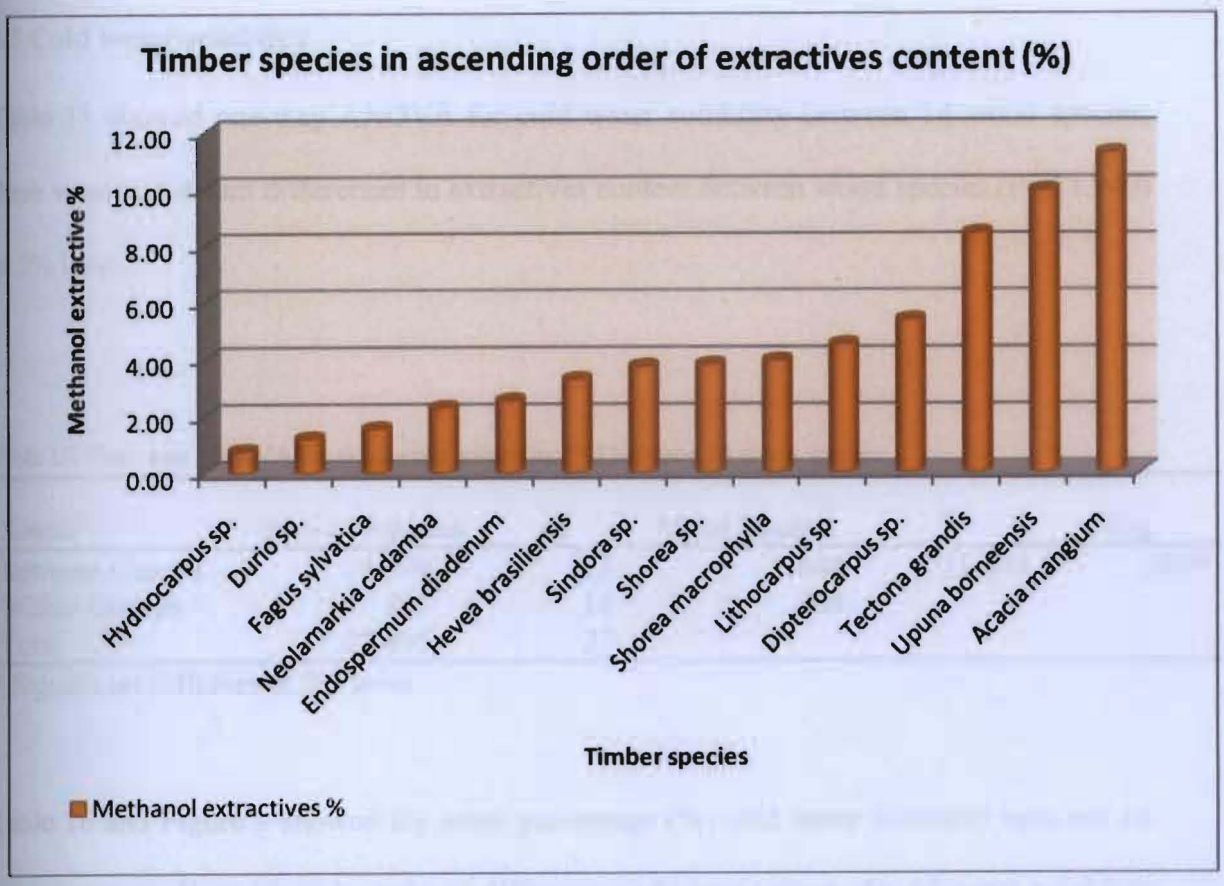


Figure 8: Comparison of methanol extractive contents (%) of 14 timber species in ascending order

4.5 Cold water solubility

Table 15 showed one-way ANOVA for cold water solubility between 14 wood species, there were significant differences in extractives content between wood species (F= 31.949) at 5% level.

Table 15: One- way ANOVA for cold water solubility (%) between 14 wood species

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	26.599	13	2.046	31.949	.000*
Within Groups	.897	14	.064		
Total	27.495	27			

* Significant different at 5% level

Table 16 and Figure 9 showed the mean percentage (%) cold water solubility between 14 wood species. Their likely significant differences of mean values of cold water solubility were compared using Duncan's multiple range test. The highest mean solubility was 5.6 % in *Acacia mangium* while the lowest mean percentage was 2.3 % in *Durio* sp. (Durian) and *Hydnoscarpus* sp. (Senumpul). Some species showed significantly differences ($P<0.05$) in cold water solubility. For example, *Lithocarpus* sp. (Mempening), *Shorea macrophylla* (Engkabang jantong) and *Upuna borneensis* (Penyau) were quite similar statistically (3.8% - 4.3%), while that of *Dipterocarpus* sp. (Keruing), *Endospermum diadenum* (Terbulan), *Neolarmarkia cadamba* (Kelampayan), *Shorea* sp. (Light Red Meranti) and *Fagus sylvatica* (European beech) were also quite similar as a group ($P<0.05$).

Table 16: Mean percentage (%) cold water solubility between 14 wood species

Species	Substrate	Mean cold water solubility (%)
Dipterocarpus sp. (Keruing)	Heartwood	3.0 *b* (0.4)
Durio sp. (Durian)	Sapwood / Heartwood?	2.3 *a* (0.1)
Endospermum diadenum (Terbulan)	Sapwood	3.2 *bc* (0.5)
Hydnocarpus sp. (Senumpul)	Sapwood	2.3 *a* (0.2)
Lithocarpus sp. (Mempening)	Heartwood	4.3 *def* (0.01)
Neolarmarkia cadamba (Kelampayan)	Sapwood	3.3 *bc* (0.03)
Shorea macrophylla (Engkabang jantong)	Sapwood / Heartwood?	3.8 *cd* (0.4)
Shorea sp. (Light Red Meranti)	Sapwood / Heartwood?	3.4 *bc* (0.1)
Sindora sp. (Sepetir)	Heartwood	4.5 *ef* (0.2)
Upuna borneensis (Penyau)	Heartwood	4.1 *de* (0.2)
Acacia mangium (Acacia mangium)	Heartwood	5.6 *g* (0.4)
Fagus sylvatica (European beech)	Sapwood	3.3 *bc* (0.2)
Hevea brasiliensis (Rubberwood)	Sapwood	5.4 *g* (0.1)
Tectona grandis (Teak)	Heartwood	4.7 *f* (0.3)

?= Sapwood or heartwood not clearly differentiated
The mean value sharing the same italized letter does not differ significantly (at 5% level)
Standard deviation value for each mean is shown in parentheses
Mean value (replication, n= 2) compared using Duncan's multiple range test

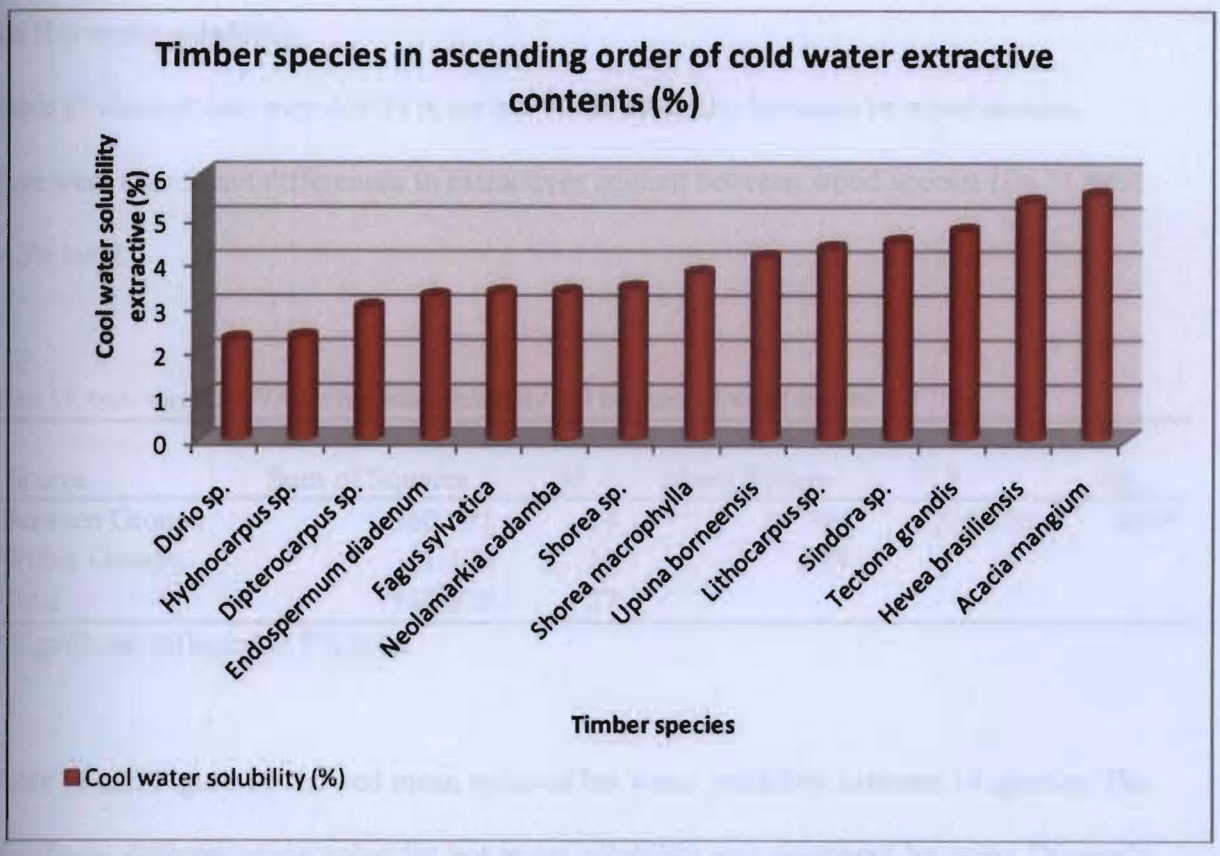


Figure 9: Comparison of cold water solubility (%) of 14 timber species in ascending order

.6 Hot water solubility

able 17 showed one-way ANOVA for hot water solubility between 14 wood species, ere were significant differences in extractives content between wood species (F= 31.949) 5% level.

able 17: One- way ANOVA for hot water solubility (%) between 14 wood species

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	360.097	13	27.700	206.330	.000*
Within Groups	1.879	14	.134		
Total	361.976	27			

Significant different at 5% level

able 18 and Figure 10 showed mean value of hot water solubility between 14 species. The gnificant different mean value for hot water solubility was compared by using Duncan's ultiple range test. The highest mean solubility was 17.4 % in *Hevea brasiliensis* Rubberwood) while the lowest mean percentage was 2.6% in *Hydnoscarpus* sp. Senumpul). Some species showed significantly difference (P<0.05) in hot water solubility. or example, *Endospermum diadenum* (Terbulan), *Neolarmarkia cadamba* (Kelampayan) nd *Shorea macrophylla* (Engkabang jantong) were quite similar statistically (4.6% - 2%), while that of *Dipterocarpus* sp. (Keruing), *Upuna borneensis* (Penyau) and *Fagus lvatica* (European beech) were also quite similar as a group (P<0.05).

Table 18: Mean percentage (%) hot water solubility between 14 wood species

Species	Substrate	Mean hot water solubility (%)
Dipterocarpus sp. (Keruing)	Heartwood	5.6 *def* (0.1)
Durio sp. (Durian)	Sapwood / Heartwood?	3.5 *b* (0.1)
Endospermum diadenum (Terbulan)	Sapwood	5.0 *cd* (0.3)
Hydnocarpus sp. (Senumpul)	Sapwood	2.6 *a* (0.2)
Lithocarpus sp. (Mempening)	Heartwood	7.0 *g* (0.6)
Neolarmarkia cadamba (Kelampayan)	Sapwood	4.6 *c* (0.1)
Shorea macrophylla (Engkabang jantong)	Sapwood / Heartwood?	5.2 *cde* (0.1)
Shorea sp. (Light Red Meranti)	Sapwood / Heartwood?	5.4 *de* (0.3)
Sindora sp. (Sepetir)	Heartwood	8.0 *h* (0.03)
Upuna borneensis (Penyau)	Heartwood	6.3 *fg* (0.2)
Acacia mangium (Acacia mangium)	Heartwood	11.6 *i* (1.1)
Fagus sylvatica (European beech)	Sapwood	6.0 *ef* (0.1)
Hevea brasiliensis (Rubberwood)	Sapwood	17.4 *j* (0.3)
Tectona grandis (Teak)	Heartwood	7.0 *g* (0.05)

?= Sapwood or heartwood not clearly differentiated
The mean value sharing the same italized letter does not differ significantly (at 5% level)
Standard deviation value for each mean is shown in parentheses
Mean value (replication, n= 2) compared using Duncan's multiple range test

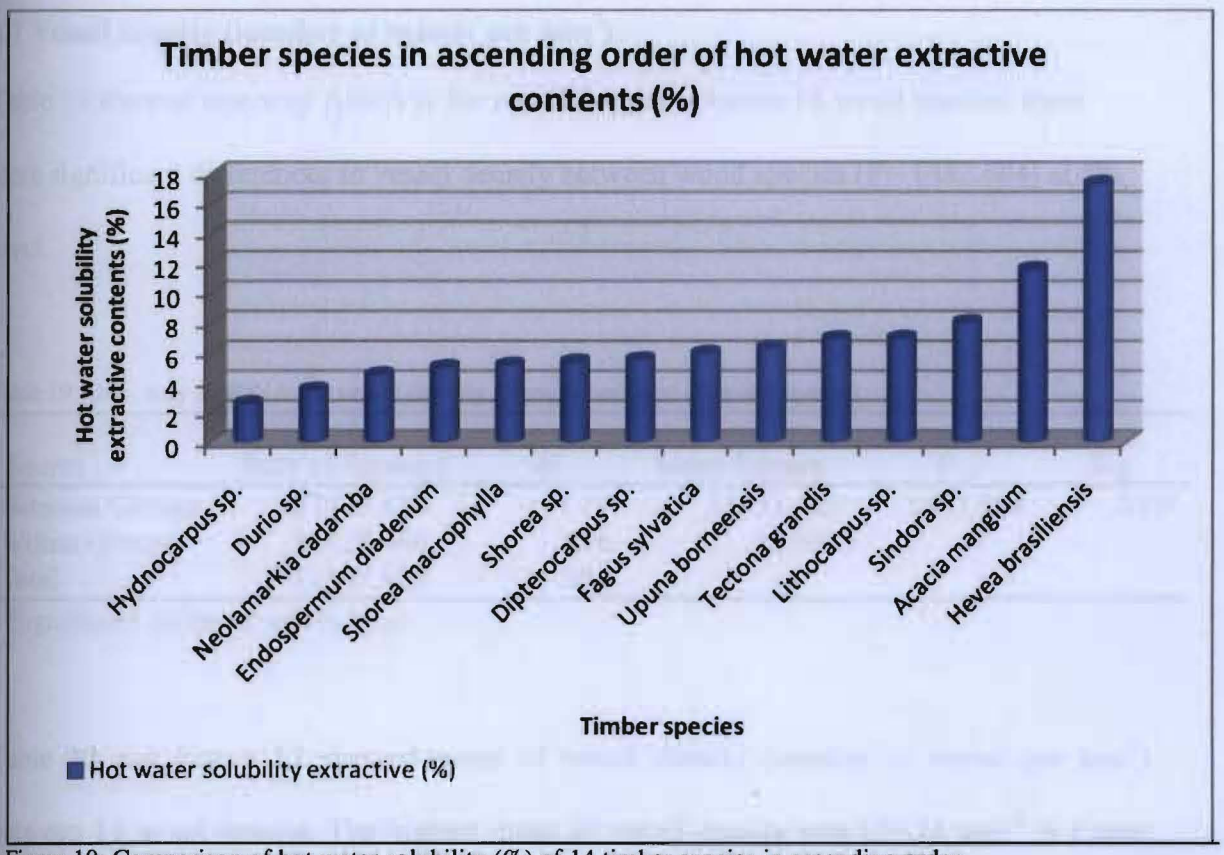


Figure 10: Comparison of hot water solubility (%) of 14 timber species in ascending order

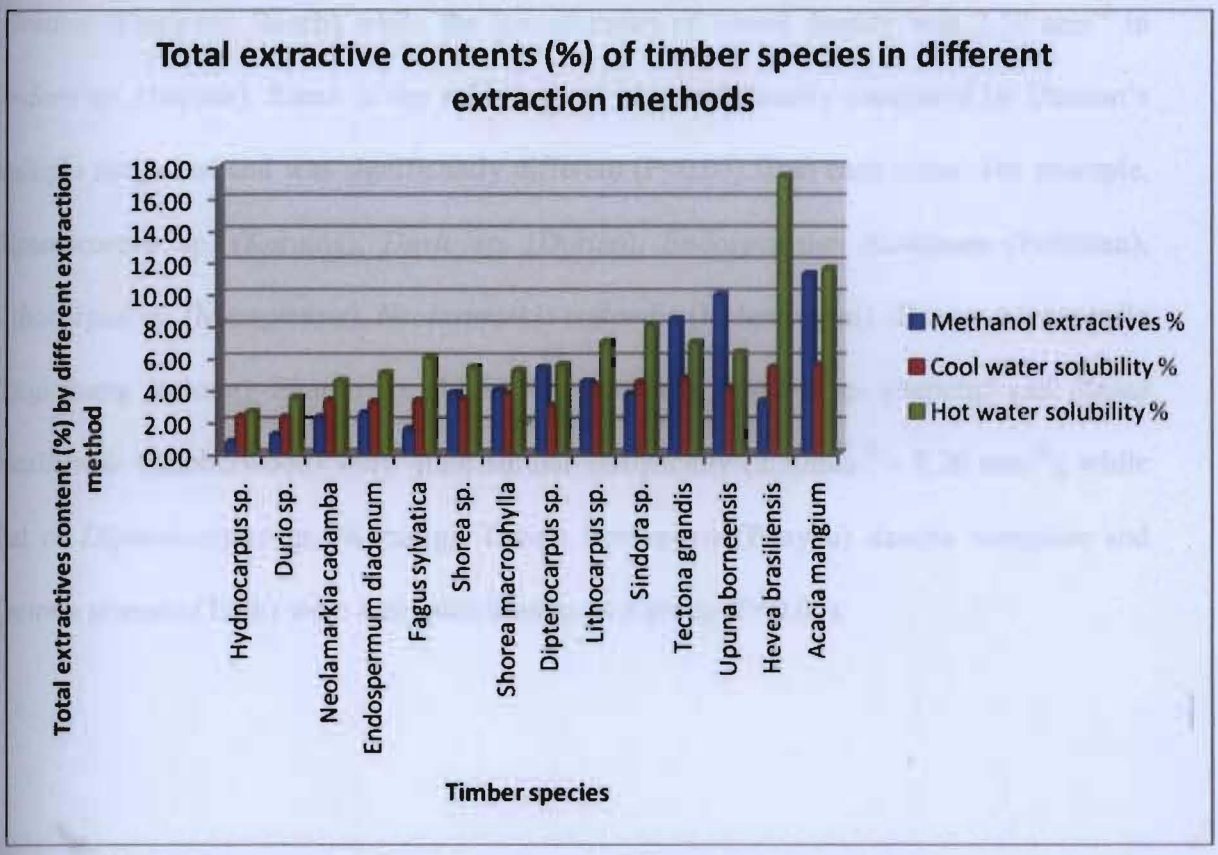


Figure 11: Extractive contents (%) of 14 timber species in different extraction ways

Table 20: Mean value of vessel density (#/mm²) between 14 wood species

Species	Mean of vessel density (#/mm^2)
Dipterocarpus sp. (Keruing)	5.26 *abc* (0.98)
Durio sp. (Durian)	3.10 *a* (0.79)
Endospermum diadenum (Terbulan)	4.28 *ab* (1.18)
Hydnocarpus sp. (Senumpul)	14.39 *d* (2.23)
Lithocarpus sp. (Mempening)	3.34 *a* (1.16)
Neolarmarkia cadamba (Kelampayan)	2.57 *a* (0.53)
Shorea macrophylla (Engkabang jantong)	3.07 *a* (0.43)
Shorea sp. (Light Red Meranti)	4.01 *ab* (1.01)
Sindora sp. (Sepetir)	2.50 *a* (0.74)
Upuna borneensis (Penyau)	6.21 *bc* (1.69)
Acacia mangium (Acacia mangium)	6.98 *c* (0.98)
Fagus sylvatica (European beech)	126.24 *e* (21.76)
Hevea brasiliensis (Rubberwood)	2.74 *a* (0.69)
Tectona grandis (Teak)	6.98 *c* (1.83)

The mean value sharing the same italized letter does not differ significantly (at 5% level)
Standard deviation value for each mean is shown in parentheses
Mean value (replication, n= 50) compared using Duncan's multiple range test

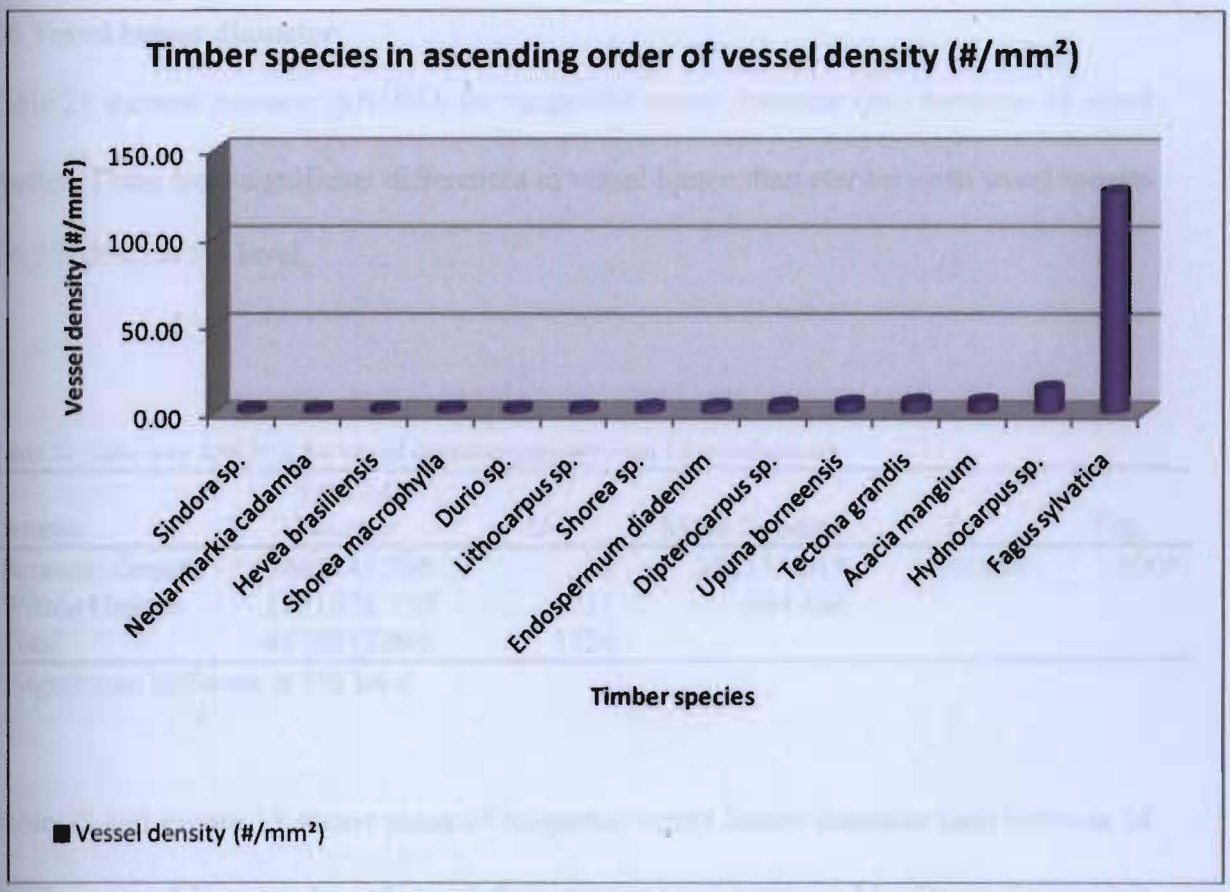


Figure 12: Timber species in ascending order of vessel density (#/mm²)

.8 Vessel lumen diameter

Table 21 showed one-way ANOVA for tangential vessel diameter (µm) between 14 wood species. There were significant differences in vessel lumen diameter between wood species (F= 382.992) at 5% level.

Table 21: One- way ANOVA for vessel diameter (µm) between 14 wood species

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	3407742.236	13	262134.018	382.992	.000*
Within Groups	1171070.750	1711	684.436		
Total	4578812.986	1724			

* Significant different at 5% level

Table 22 and Figure 13 shows mean of tangential vessel lumen diameter (µm) between 14 wood species. Mean number of vessel diameter (µm) was compared by Duncan's multiple range test. Species of *Lithocarpus* sp. (Mempening) has the highest mean value of vessel lumen diameter with 209.32 µm while *Fagus sylvatica* (European Beech) has the lowest mean value of vessel diameter with 47.68 µm. The mean values of vessel lumen diameter in some species was significantly different (P<0.05) from each other. For example, *Durio* sp. (Durian), *Neolarmarkia cadamba* (Kelampayan) and *Hevea brasiliensis* (Rubberwood) were quite similar statistically (190.88 µm – 197.36 µm), while that of *Dipterocarpus* sp. (Keruing), *Shorea* sp. (Light Red Meranti), *Upuna borneensis* (Penyau) and *Tectona grandis* (Teak) were also quite similar as a group (P<0.05).

Table 22: Mean value of vessel diameter (μm) between 14 wood species

Species	Mean vessel diameter (μm)
Dipterocarpus sp. (Keruing)	177.12 *e* (19.26)
Durio sp. (Durian)	197.36 *gh* (20.95)
Endospermum diadenum (Terbulan)	200.48 *h* (20.55)
Hydnocarpus sp. (Senumpul)	91.92 *b* (16.52)
Lithocarpus sp. (Mempening)	209.32 *i* (27.01)
Neolarmarkia cadamba (Kelampayan)	196.44 *gh* (17.14)
Shorea macrophylla (Engkabang jantong)	188.52 *f* (21.08)
Shorea sp. (Light Red Meranti)	178.08 *e* (17.72)
Sindora sp. (Sepetir)	134.36 *c* (24.20)
Upuna borneensis (Penyau)	177.68 *e* (16.93)
Acacia mangium (Acacia mangium)	153.15 *d* (16.51)
Fagus sylvatica (European beech)	47.68 *a* (5.84)
Hevea brasiliensis (Rubberwood)	190.88 *fg* (20.31)
Tectona grandis (Teak)	177.56 *e* (67.98)

The mean value sharing the same italized letter does not differ significantly (at 5% level)
Standard deviation value for each mean is shown in parentheses
Mean value (replication, n= 125) compared using Duncan's multiple range test

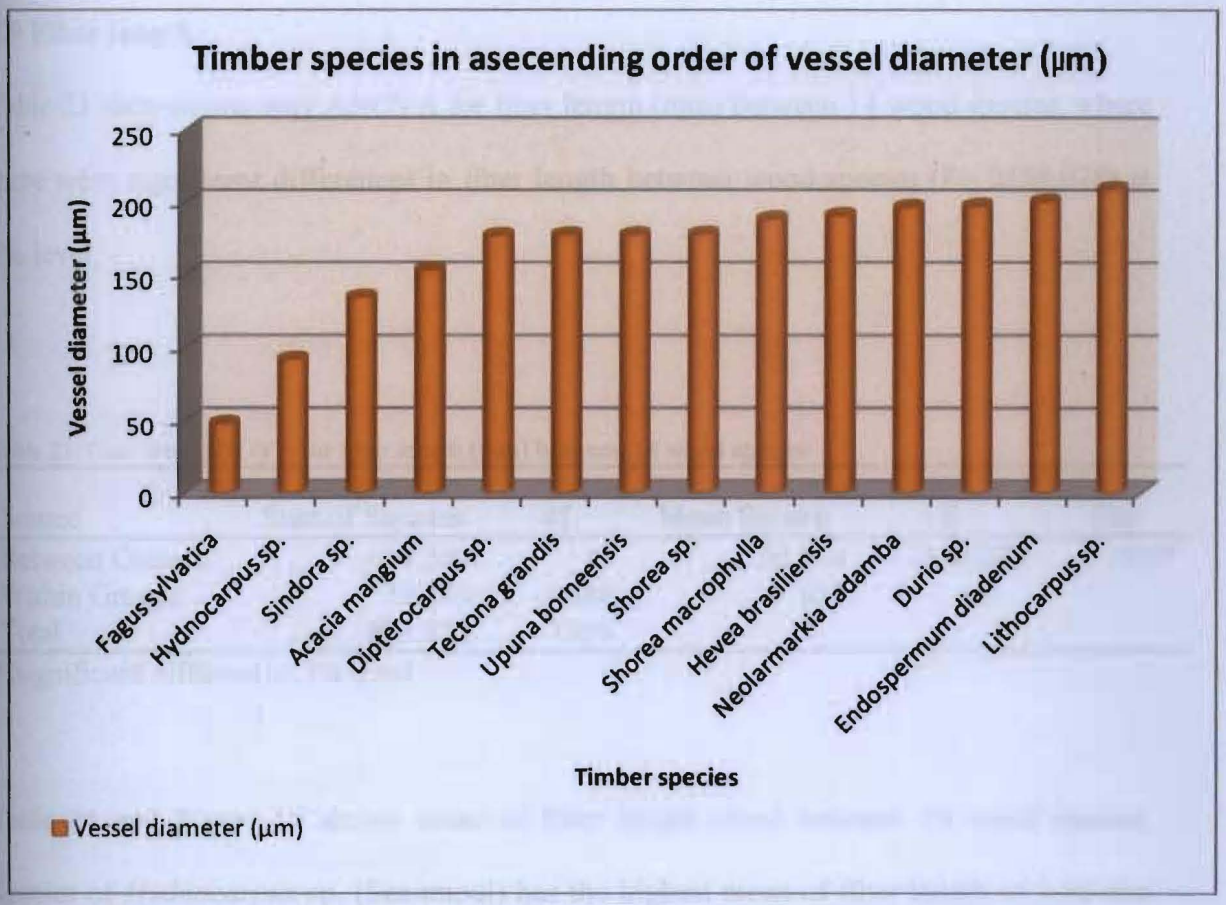


Figure 13: Timber species in ascending order of vessel diameter (µm)

4.9 Fiber length

Table 23 showed one-way ANOVA for fiber length (mm) between 14 wood species, where there were significant differences in fiber length between wood species (F= 2158.078) at 5% level.

Table 23: One- way ANOVA for fiber length (mm) between 14 wood species

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	654.599	13	50.354	2158.078	.000*
Within Groups	39.339	1686	.023		
Total	693.938	1699			

* Significant different at 5% level

Table 24 and Figure 14 shows mean of fiber length (mm) between 14 wood species. Species of *Hydnocarpus* sp. (Senumpul) has the highest mean of fiber length of 3.55 mm while *Neolarmarkia cadamba* (Kelampayan) and *Fagus sylvatica* (European Beech) has the lowest mean of fiber length of 1.14 mm. All the mean fiber length value between species were compared by using Duncan's multiple range test and for some species, the mean value were significantly different ($P<0.05$) from each other. For example, *Shorea macrophylla* (Engkabang jantong) and *Shorea* sp. (Light Red Meranti) were quite similar statistically (1.25 mm – 1.28 mm) at $P<0.05$.

Table 24: Mean value of fiber length (mm) between 14 wood species

Species	Mean fiber length (mm)
Dipterocarpus sp. (Keruing)	1.73 *h*
	(0.12)
Durio sp. (Durian)	1.68 *g*
	(0.16)
Endospermum diadenum (Terbulan)	2.34 *i*
	(0.22)
Hydnocarpus sp. (Senumpul)	3.55 *j*
	(0.38)
Lithocarpus sp. (Mempening)	1.46 *e*
	(0.12)
Neolarmarkia cadamba (Kelampayan)	1.14 *a*
	(0.07)
Shorea macrophylla (Engkabang jantong)	1.28 *c*
	(0.08)
Shorea sp. (Light Red Meranti)	1.25 *c*
	(0.07)
Sindora sp. (Sepetir)	1.37 *d*
	(0.08)
Upuna borneensis (Penyau)	1.46 *e*
	(0.11)
Acacia mangium (Acacia mangium)	1.19 *b*
	(0.06)
Fagus sylvatica (European beech)	1.14 *a*
	(0.09)
Hevea brasiliensis (Rubberwood)	1.63 *f*
	(0.13)
Tectona grandis (Teak)	1.46 *e*
	(0.10)

The mean value sharing the same italized letter does not differ significantly (at 5% level)
Standard deviation value for each mean is shown in parentheses
Mean value (replication, n= 125) compared using Duncan's multiple range test

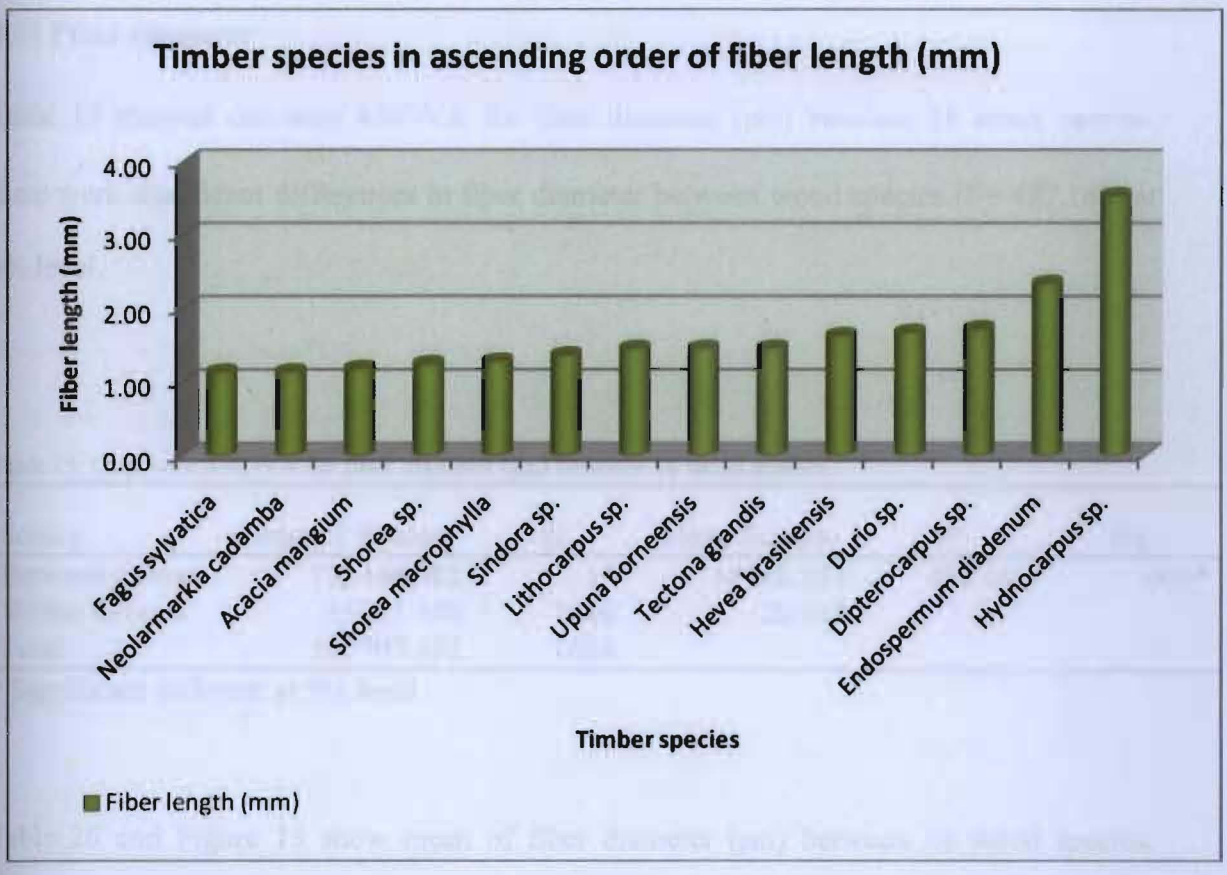


Figure 14: Timber species in ascending order of fiber length (mm)

10 Fiber diameter

ıble 25 showed one-way ANOVA for fiber diameter (µm) between 14 wood species, ere were significant differences in fiber diameter between wood species (F= 487.140) at % level.

ble 25: One- way ANOVA for fiber diameter (µm) between 14 wood species

ource	Sum of Squares	df	Mean Square	F	Sig.
etween Groups	132446.382	13	10188.183	487.140	.000*
ithin Groups	35261.500	1686	20.914		
otal	167707.882	1699			

Significant different at 5% level

ıble 26 and Figure 15 show mean of fiber diameter (µm) between 14 wood species. ecies of *Endospermum diadenum* (Terbulan) has the highest mean fiber diameter of .28 µm width while *Upuna borneensis* (Penyau) has the lowest mean fiber diameter of .12 µm width. All the mean fiber diameter was compared by using Duncan's multiple nge test and some mean values were significantly different (P<0.05) from each other. For ample, *Upuna borneensis* (Penyau) and *Acacia mangium* were quite similar statistically 6.15 µm – 17.12 µm), while another group comprising *Dipterocarpus* sp. (Keruing), *thocarpus* sp. (Mempening) and *Sindora* sp. (Sepetir) were also quite similar (P<0.05).

ble 26: Mean value of fiber diamter (μm) between 14 wood species

pecies	Mean fiber diameter (μm)
Dipterocarpus sp. (Keruing)	22.04 *c* (3.54)
Durio sp. (Durian)	24.64 *d* (5.24)
Endospermum diadenum (Terbulan)	46.28 *i* (7.27)
Hydnocarpus sp. (Senumpul)	44.72 *h* (7.02)
Lithocarpus sp. (Mempening)	22.28 *c* (4.33)
Neolarmarkia cadamba (Kelampayan)	28.44 *f* (4.04)
Shorea macrophylla (Engkabang jantong)	31.65 *g* (4.09)
Shorea sp. (Light Red Meranti)	31.00 *g* (4.02)
Sindora sp. (Sepetir)	22.72 *c* (3.39)
Upuna borneensis (Penyau)	17.12 *a* (2.86)
Acacia mangium (Acacia mangium)	16.15 *a* (2.55)
Fagus sylvatica (European beech)	18.56 *b* (3.23)
Hevea brasiliensis (Rubberwood)	24.84 *d* (4.40)
Tectona grandis (Teak)	26.80 *e* (4.81)

e mean value sharing the same italized letter does not differ significantly (at 5% level)
ndard deviation value for each mean is shown in parentheses
ean value (replication, n= 125) compared using Duncan's multiple range test

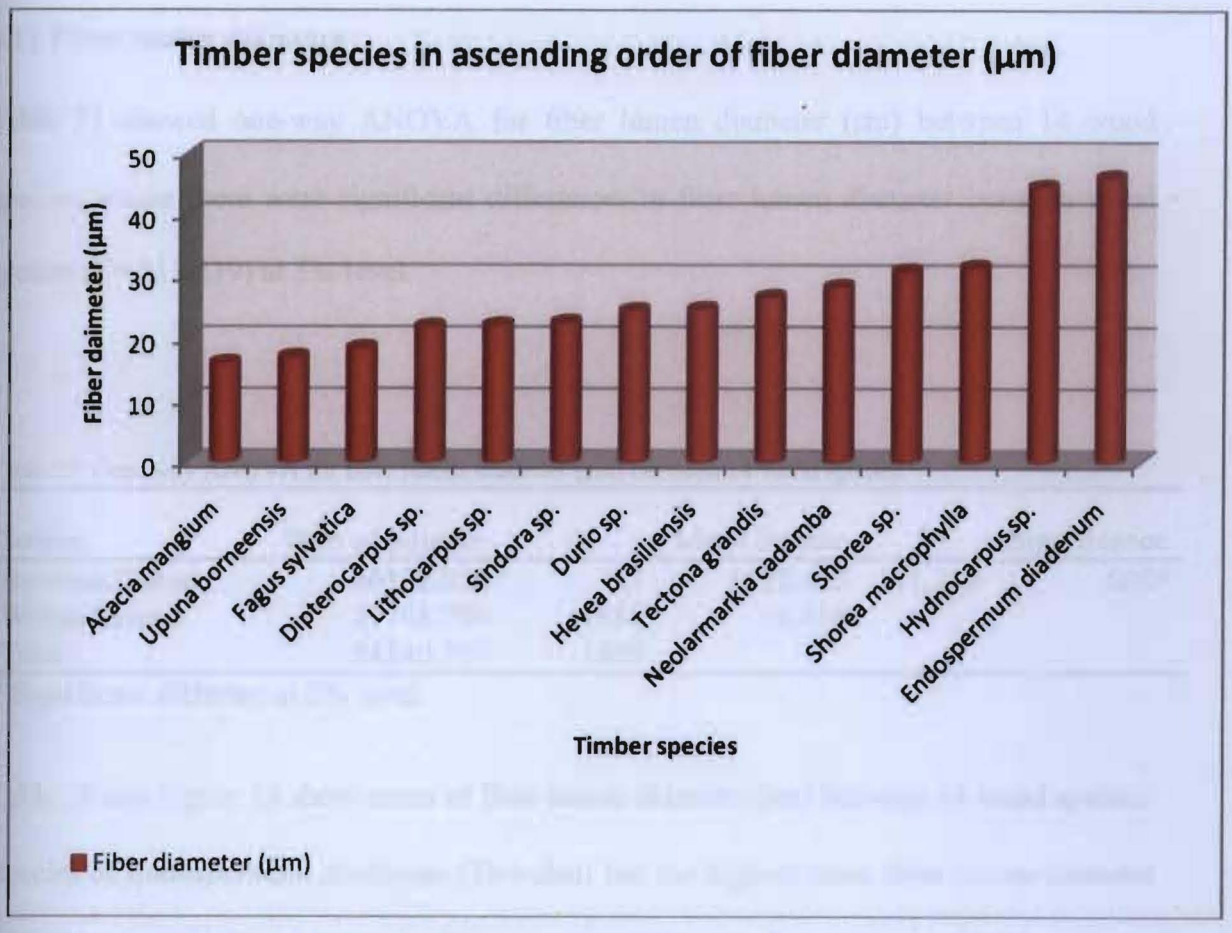


Figure 15: Timber species in ascending order of fiber diameter (µm)

4.11 Fiber lumen diameter

Table 27 showed one-way ANOVA for fiber lumen diameter (μm) between 14 wood species, where there were significant differences in fiber lumen diameter between wood species (F= 311.239) at 5% level.

Table 27: One- way ANOVA for fiber lumen diameter (μm) between 14 wood species

Source	Sum of Squares	df	Mean Square	F	Significance
Between Groups	66592.050	13	5122.465	311.239	.000*
Within Groups	27748.700	1686	16.458		
Total	94340.750	1699			

* Significant different at 5% level

Table 28 and Figure 16 show mean of fiber lumen diameter (μm) between 14 wood species. Species of *Endospermum diadenum* (Terbulan) has the highest mean fiber lumen diameter of 32.36 μm while *Fagus sylvatica* (European beech) has the lowest mean of 9.28 μm thick. All the mean value of fiber wall thickness were compare by using Duncan's multiple range test and some species showed significantly different ($P<0.05$) values from each other. For example, *Acacia mangium* and *Fagus sylvatica* (European beech) were quite similar statistically (9.55 μm – 9.28 μm), while that of *Dipterocarpus* sp. (Keruing) and *Sindora* sp. (Sepetir) were also quite similar in another group ($P<0.05$).

Table 28: Mean value of fiber lumen diameter (μm) between 14 wood species

Species	Mean fiber lumen diameter (μm)
Dipterocarpus sp. (Keruing)	14.40 *ef* (3.28)
Durio sp. (Durian)	12.64 *cd* (4.24)
Endospermum diadenum (Terbulan)	32.36 *k* (6.49)
Hydnocarpus sp. (Senumpul)	16.92 *g* (5.88)
Lithocarpus sp. (Mempening)	11.76 *c* (3.88)
Neolarmarkia cadamba (Kelampayan)	21.00 *i* (3.59)
Shorea macrophylla (Engkabang jantong)	22.95 *j* (4.21)
Shorea sp. (Light Red Meranti)	23.04 *j* (3.75)
Sindora sp. (Sepetir)	13.60 *de* (3.45)
Upuna borneensis (Penyau)	10.48 *b* (2.49)
Acacia mangium (Acacia mangium)	9.55 *ab* (2.02)
Fagus sylvatica (European beech)	9.28 *a* (3.28)
Hevea brasiliensis (Rubberwood)	14.88 *f* (3.78)
Tectona grandis (Teak)	18.72 *h* (3.96)

The mean value sharing the same italized letter does not differ significantly (at 5% level)
Standard deviation value for each mean is shown in parentheses
Mean value (replication, n= 125) compared using Duncan's multiple range test

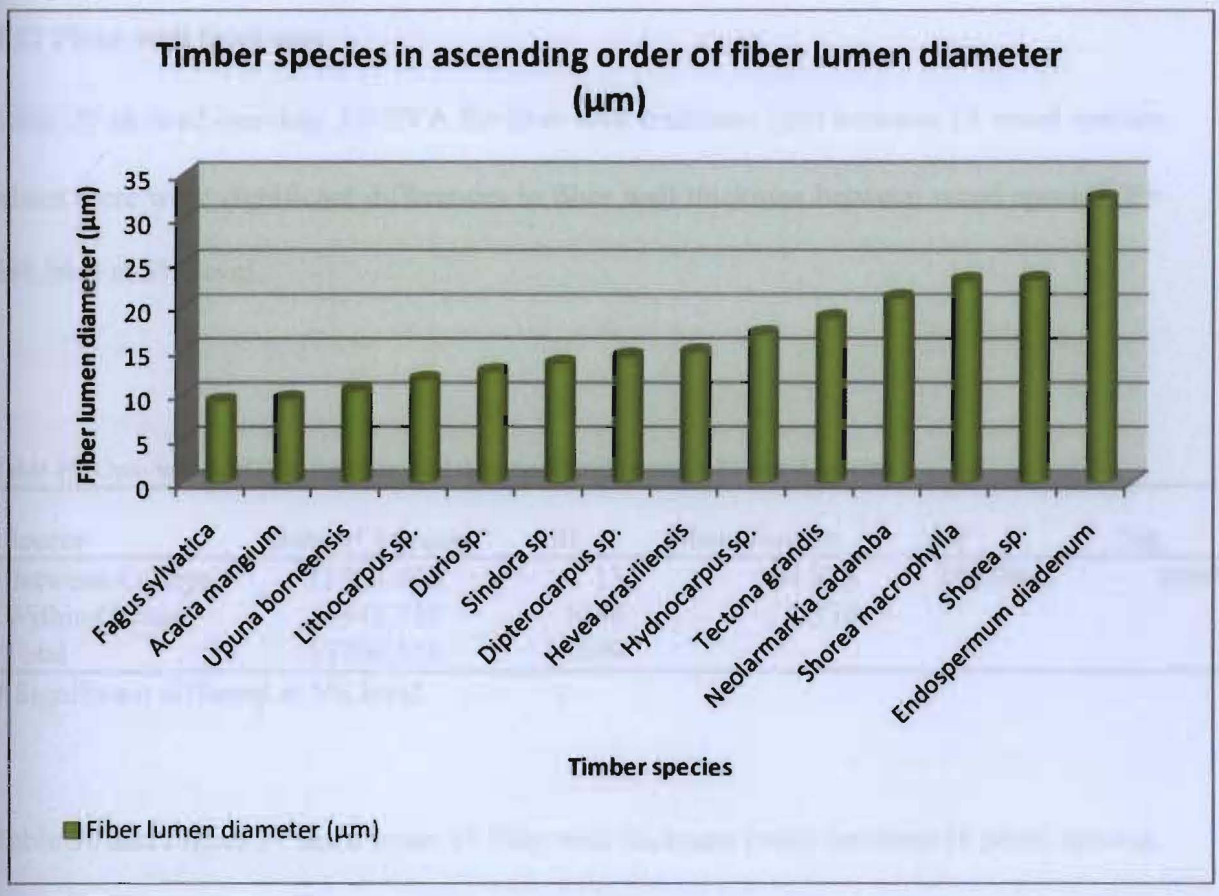


Figure 16: Timber species in ascending order of fiber lumen diameter (µm)

4.12 Fiber wall thickness

Table 29 showed one-way ANOVA for fiber wall thickness (μm) between 14 wood species, where there were significant differences in fiber wall thickness between wood species (F= 386.944) at 5% level.

Table 29: One- way ANOVA for fiber wall thickness (μm) between 14 wood species

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	11763.408	13	904.878	386.944	.000*
Within Groups	3942.750	1686	2.339		
Total	15706.158	1699			

* Significant different at 5% level

Table 30 and Figure 17 show mean of fiber wall thickness (mm) between 14 wood species. Species of *Hydnocarpus* sp. (Senumpul) has the highest mean fiber wall thickness of 13.90 μm while *Acacia mangium* has the lowest mean of 3.30 μm thick. All the mean value of fiber wall thickness were compare by using Duncan's multiple range test and some species showed significantly different (P<0.05) values from each other. For example, *Dipterocarpus* sp. (Keruing), *Neolarmarkia cadamba* (Kelampayan), *Shorea* sp. (Light Red Meranti) and *Tectona grandis* (Teak) were quite similar statistically (3.72 μm – 4.04 μm), while that of *Shorea macrophylla* (Engkabang jantong), *Sindora* sp. (Sepetir) and *Fagus sylvatica* (European beech) were also quite similar as a group (P<0.05).

Table 30: Mean value of fiber wall thickness (μm) between 14 wood species

Species	Mean fiber wall thickness (μm)
Dipterocarpus sp. (Keruing)	3.82 *b* (1.25)
Durio sp. (Durian)	6.00 *g* (1.56)
Endospermum diadenum (Terbulan)	6.96 *h* (1.67)
Hydnocarpus sp. (Senumpul)	13.90 *i* (2.63)
Lithocarpus sp. (Mempening)	5.26 *f* (1.76)
Neolarmarkia cadamba (Kelampayan)	3.72 *b* (1.33)
Shorea macrophylla (Engkabang jantong)	4.35 *cd* (1.36)
Shorea sp. (Light Red Meranti)	3.98 *bc* (1.27)
Sindora sp. (Sepetir)	4.56 *d* (1.06)
Upuna borneensis (Penyau)	3.32 *a* (1.18)
Acacia mangium (Acacia mangium)	3.30 *a* (1.22)
Fagus sylvatica (European beech)	4.64 *de* (1.44)
Hevea brasiliensis (Rubberwood)	4.98 *ef* (1.57)
Tectona grandis (Teak)	4.04 *bc* (1.37)

The mean value sharing the same italized letter does not differ significantly (at 5% level)
Standard deviation value for each mean is shown in parentheses
Mean value (replication, n= 125) compared using Duncan's multiple range test

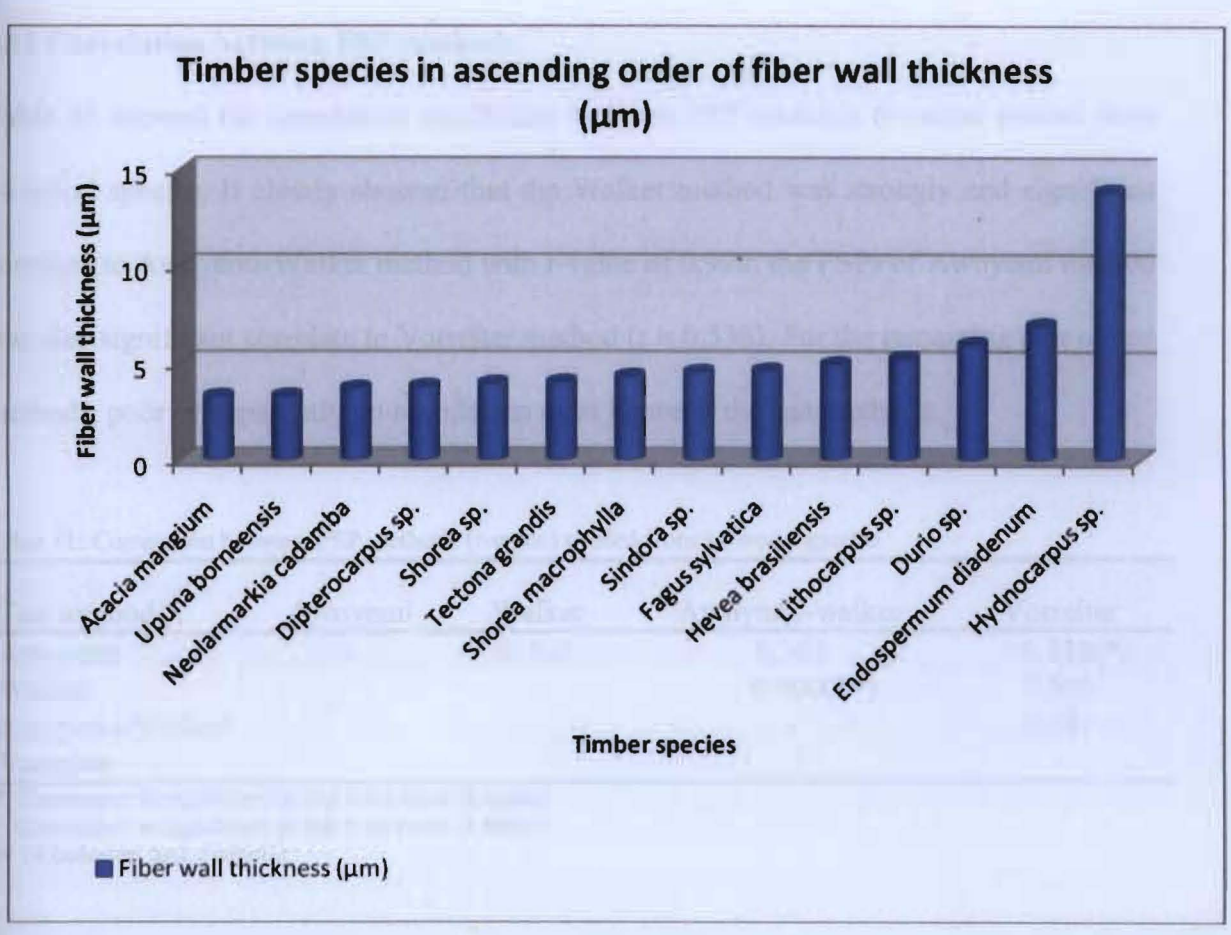


Figure 17: Timber species in ascending order of fiber wall thickness (µm)

4.13 Correlation between FSP methods

Table 31 showed the correlation coefficient between FSP methods (r-value) pooled from 14 wood species. It clearly showed that the Walker method was strongly and significant correlate to Awoyemi-Walker method with r-value of 0.990; the FSPs of Awoyemi method was also significant correlate to Vorreiter method (r = 0.538). For the remaining pair of test methods, poor or apparently no correlation exist between the test methods.

Table 31: Correlation between FSP methods (r-value) pooled from 14 wood species

Test method	Awoyemi	Walker	Awoyemi-walker	Vorreiter
Awoyemi	-	0.305	0.262	0.538(*)
Walker		-	0.990(**)	0.501
Awoyemi-Walker			-	0.381
Vorreiter				-

** Correlation is significant at the 0.01 level (2-tailed)
* Correlation is significant at the 0.05 level (2-tailed)
n= 14 between test methods

4.14 Correlation of FSP to physical properties, extractive contents and anatomical properties

Table 32 shows the correlation coefficients between fiber saturation point determined by each method and the properties of wood as well as the relationship between properties from 14 timber species. Not all the test methods were significant correlated with wood properties at $P<0.05$.

Through the correlation table, it clearly showed that the FSP in Awoyemi method, Walker method, and Vorreiter method were significant negatively correlated with basic density except that of the Awoyemi-Walker method; while FSP values in Walker method and Awoyemi-Walker method were significantly negative correlate with methanol extractive contents (r = -0.0628 and r = -0.625 respectively). Also, the FSP of 4 methods showed significantly positive correlation with water permeability, while FSPs in Walker method

and Awoyemi method showed significantly positive correlation with vessel density (r = 0.541 and r = 0.630 respectively). For the remaining properties, the FSP values show positive or negative correlation with wood properties depending on the method used but not significantly.

Between wood properties, basic density showed significantly negative correlation with water permeability (r = -0.860) and with fiber lumen diameter (r = -0.719), while significant negative correlation also exist between the pair properties of solvent extractives and fiber diameter (r = -0.535), vessel density and vessel diameter (r = - 0.787). Also, significant positive correlation exists between pair properties of solvent extractive and cold water solubility (r = 0.667), cold water solubility and hot water solubility (r = 0.843), fiber length and fiber diameter (r = 0.737), fiber length and fiber wall thickness (r = 0.942), fiber diameter and fiber lumen diameter (r = 0.813), fiber diameter and fiber wall thickness (r = 0.713) at 0.01 and 0.05 level. For the remaining wood properties, no significant correlations exist (positive or negative) were found.

elation between fiber saturation point to the properties of wood and the relationship of properties within timber species

	B. density	W. permeability	M. extractives	C. solubility	H. solubility	V. density	V. diameter	F. length	F. diameter	F.L. diameter	F.W. thickness
	-0.645*	0.662**	-0.434	0.086	0.263	0.237	-0.024	-0.017	0.413	0.558*	0.027
	-0.577*	0.662**	-0.628*	-0.514	-0.362	0.541*	-0.350	-0.173	0.127	0.177	0.001
	-0.469	0.576*	-0.625*	-0.529	-0.363	0.630*	-0.438	-0.149	0.070	0.075	0.028
	-0.977**	0.807**	-0.287	-0.101	-0.161	-0.154	0.293	-0.262	0.412	0.746**	-0.202
	-	-0.860**	0.380	0.095	0.116	0.024	-0.173	0.267	-0.411	-0.719**	0.171
ity		-	-0.562*	-0.271	-0.142	0.026	0.105	-0.025	0.533*	0.726**	0.028
s			-	0.667**	0.349	-0.250	0.204	-0.374	-0.535*	-0.311	-0.531
				-	0.843**	-0.159	0.171	-0.477	-0.488	-0.260	-0.513
					-	-0.088	0.124	-0.303	-0.407	-0.286	-0.344
						-	-0.787**	-0.146	-0.229	-0.330	0.009
							-	-0.214	0.058	0.381	-0.360
								-	0.737**	0.253	0.942**
									-	0.813**	0.713**
										-	0.171
ss											-

significant at the 0.05 level (2-tailed).
s significant at the 0.01 level (2-tailed).

5.0 Discussion

In the study of water permeability on 14 timber species, *Upuna borneensis* (Penyau) was low in water permeability (24.71%) while *Shorea* spp. (Light Red Meranti) and *Endospermum diadenum* (Terbulan) revealed to have highest water permeability, of 181.60% and 179.29% respectively.

When all the fourteen species' wood blocks were subjected to water permeability determination in which the wood blocks were soaked in tap water and immediately vacuated in water for 15 minutes of treatment; it is found that in some species, the wood blocks sank to the bottom while other blocks floated on the surface of water. Through observation, ten replicates of water saturated wood blocks of *Shorea macrophylla* (Engkabang jantong) floated on the surface of water after the vacuum-atmospheric pressure treatment. This might be either (i) water is unable to retain in the fiber cell wall or (ii) other cells may also block entry of water due to trapped air spzces in the cells despite vacuum treatment. Walker (1993) stated that in a living tree, the hydroxyl groups in the amorphous regions of the cell wall are able to form hydrogen bonds with adsorbed water and with the other cell wall constituents. The individual cell walls constituents draw close together by formation of new strong hydrogen bonds among themselves during desorption. Subsequently, when rehydration is imposed onto the same wood, not all the newly form hydrogen bonds can be easily broken and thus a decrease in ability to bond with water molecule.

Furthermore, the rate of re-absorption might be slowed after a previous desorption phase. This is due to the adsorbed water molecules having to penetrate and push apart the consolidated cell wall constituents and replace some of the newly form intermolecular

hydrogen bonds with re-adsorbed water molecule (Walker, 1993). Also, presence of atmosphere bubble in the cell wall during air drying also can retarded and blocked the uptake of water during pressure treatment. In addition, some wood has repellency properties whereby the wood is able to repel water from coming into its body and contact with its cell, probably due to the presence of wood extractive in the cell lumen or cell walls. Water permeability is also cause by substrate feature of wood as heartwood or sapwood. According to Durbak *et al.* (1998), permeability in sapwood portion is considered more than heartwood portion and it is found in one instance that heartwood is practically zero in the function of permeability.

Wood density varies due to systematic variations within a single tree, with genetic and environmental variation between trees of the same species (Dinwoodie, 1989); growth conditions, part of the tree measured, plantation sites, climate, and geographic location (Haygreen & Bowyer, 1996, cited, Jem, 2008). The wood density between wood species in this study was significantly different. The substrate of wood as heartwood and sapwood has a relation to the wood density. For example in the 14 timber species, the heartwood of *Upuna borneensis* (Penyau) was the densest species (795.529 kg/m^3) compare to the sapwood of *Neolarmarkia cadamba* (Kelampayan) with the basic density of 276.959 kg/m^3. Interspecies differences in wood density affect other properties of timber species, such as water permeability.

In wood, the amount of extractives can range from 1 to 20% depending upon species and position within the tree (Uprichard, 1993). The types of compound isolated by extraction were broadly dependent upon the polarity of the solvents used for extraction. Cold water solubility provides a measurement of tannins, gums, sugars, and coloring matter in the wood; hot water solubility provide the same measurement as with cold water solubility but

with addition of starches in the wood (ASTM, 2000). In this study, both cold water and hot water soluble were differing in their value of solubility. The extractive contents of hot water solubility were higher compared to cold water solubility (Figure 11). Obviously the effect of high temperature, whereby cold water solubility was done at room temperature while hot water solubility was done at higher temperature at 121° C, has hasten the leaching of extractives from wood.

The methanol extractives for most species were higher compared to cold water solubility but were lower compared to hot water solubility (Figure 11) again due to the effect of high temperature of 121^0C that had extracted out greater amounts of the extractives such as sugar and starches compared to methanol extraction. Compared to previous study by Jem (2008) on 4 types timber species which is *Acacia mangium, Neolarmarkia cadamba* (Kelampayan), *Shorea macrophylla* (Engkabang jantong) and *Endospermum diadenum* (Terbulan), the methanol extractive contents for the 4 timber species in this study were approximately same as found by Jem (Table 35). Furthermore as shown in Figure 11, species with higher percentage of extractive contents such as *Hevea brasiliensis* (Rubberwood) and *Acacia mangium* are not suitable for flooring products production, due to the extractives bleeding may happen to this kind of wood species when exposed to wetting uncoated.

Vessel density or also known as vessel proportion was measured to have knowledge about number of vessels per unit mm^2 of the timber species. Among the 14 species, *Fagus sylvatica* (European beech) was the species highest in mean vessel density which is 126.24 vessels per mm^2 following by *Hydnocarpus* sp. (Senumpul) with mean value of 14.39 vessels per mm^2. There was a big variation of vessel density between *Fagus sylvatica* (European beech) to the other 13 wood species. Under a microscope, it clearly showed that

y and abundance vessels of beech distributed and cover whole cross sections of wood sue. Beech might be unlike other temperate species, where the vessels were bigger and undant in spring and become less abundance and smaller in late autumn. In this study, vessel density for *Fagus sylvatica* was measured along the rays and growth ring. ring vessel density measurement on these 14 species, it is clearly shown that some ecies only has solitary vessels, while other species have vessels in radial multiples of two more. For example, *Lithocarpus* sp. (Mempening) has solitary vessels only, while *dospermum diadenum* (Terbulan) and *Hevea brasiliensis* (Rubberwood) have multiple ssels rather than solitary vessels. The distribution of different type of vessels was one of characteristic for identification in timber species.

e vessels or also known as pores can be relatively wide up to 0.5 mm (Dinwoodie, 1981). vessel diameter measurement, *Fagus sylvatica* (European beech) which was highest in ssel density now stand for the species lowest in vessel diameter with 47.68 µm followed *Hynocarpus* sp. with the vessel diameter of 91.92 µm. Perhaps, species with large vessel meter was significantly negatively correlated with vessel density. In this study, the ssel diameter was measured in the tangential direction of vessels in all the species as it is suitable to measure the vessel diameter from the radial direction when the vessels are sent in multiple or cluster.

ers give structural supporting to timber (Butterfield, 1993). The lengths of fiber varied m 1 – 2 mm (Dinwoodie, 1981). In this study, the fiber length in almost all species are in the range of 1 mm to 2 mm except for the species of *Endospermum diadenum* rbulan) and *Hydnocarpus* sp. (Senumpul) which have fiber length of 2.34 mm and 3.55 n respectively. In measurement of fiber diameter, *Hydnocarpus* spp. (Senumpul) and *dospermum diadenum* (Terbulan) revealed as the species highest in fiber diameter which

is 44.72μm and 46.28μm in wide. Again, obviously show that fiber length was significant positive correlate to fiber diameter. As and now, it can be assumed and suggested that fiber length will have positive correlation with fiber wall thickness where the longer the fiber the thicker the fiber wall in the wood. The assumption had been proved in measurement of fiber wall thickness, with *Hydnocarpus* sp. (Senumpul) revealed as the species highest in fiber wall thickness following by *Endospermum diadenum* (Terbulan) with 13.9 μm and 6.96 μm in thickness respectively. Overall cell growth results in longer, wider and thicker fiber cells in wood xylem.

As mentioned, fiber saturation point (FSP) refer to the point or level at which the cell cavities and lumina are fully devoid of free water though the cell walls are fully saturated with bound or adsorbed water (Negi, 1997; Walker, 1993). Through observation on the four methods conducted, Awoyemi method recorded relatively high fiber saturation point for 10 out of 14 timber species compared to the other three methods (Table 12). Theoretically, fiber saturation point for many timber species is generally the range of 25% to 35% except for some species which is low in density might have higher fiber saturation point (Walker, 1993). However, there have some species in this study had attained too high a value of fiber saturation point such as *Endospermum diadenum* (Terbulan) and *Hevea brasiliensis* (Rubberwood), achieving at the moisture content of 61.25% and 54.28% respectively as fiber saturation point values. These values are beyond the range of theoretical and are unlikely to be caused by their variation in anatomical structure alone. Yet, these two species do not have among the lowest mean basic density among the 14 species. Hence the unusually high FSP determined by the Awoyemi method may imply the unreliability of this method.

Both the Walker method and Awoyemi-Walker method actually are based on the same mathematical equation in calculating fiber saturation point; Walker method is based on basic density (Walker, 1993) while Awoyemi-Walker method is based on oven-dry density (Awoyemi, 2006). Hence the FSP values expectedly differ a little. Basic density of wood refers to the oven-dry mass (drying to constant weight at 103^0C) of wood per swollen volume of the wood while oven dry density refers to the oven-dry mass of the wood (103^0C) per oven-dry volume of the wood (Walker, 1993). Hence, oven-dry density would be higher than basic density values. Therefore, there is still not much difference in the fiber saturation point between these two methods (Table 12). It only differs by 0.5% to 4%. Most species are in the range of theoretical fiber saturation point except for the species *Upuna borneensis* (Penyau), *Acacia mangium* and *Tectona grandis* (Teak) with value of 12.52%, 12.42% and 7.87% respectively. But the moisture contents for these three species at fiber saturation point are too low. The reading of FSP for *Acacia mangium* and *Tectona grandis* (Teak) are lower than their air-dry moisture contents while the reading of FSP for *Upuna borneensis* (Penyau) is only higher 3.28% from its air dry moisture contents (Table 33). Hence the mathematical approach to determining FSP may not be so reliable for some wood species.

The fiber saturation point obtained by the Vorreiter method is a continuously decreasing function of bulk density (Vorreiter, 1963; cited, Feist & Tarkow, 1967). Bulk density is obtained by dividing the weight (at specified conditions) of the specimen by the bulk volume at the conditions (TAPPI, 1988). Thus, by applying oven-dry density into the function graph (Figure 1), the FSP on 14 species were obtained. In this method, all of the species fell in the range of the general limits of FSP between species which suggests that this method is reliable. The FSP for these species increase from denser to less denser

woods in which less dense wood have higher FSP such as *Shorea macrophylla* (Engkabang jantong), *Shorea* sp. (Light Red Meranti) and *Neolarmarkia cadamba* (Kelampayan) attaining fiber saturation points of 40.6%, 41.9% and 43.3% respectively. In correlation of FSP by Vorreiter method with the other three test methods, Awoyemi method showed significant correlation with Vorreiter method (r-value = 0.538); while Walker method and Awoyemi-Walker method showed poor correlation with Vorreiter method (r-value of 0.501 and 0.381 respectively). Significant correlation exist between Awoyemi method and Vorreiter method be agrees with the acceptance that less dense wood attained higher FSP, despite some unusual trends between density and FSP for some wood species using the Awoyemi method, where low density recorded unusually high FSP. Perhaps Vorreiter method is most reliable way to estimate FSP and Awoyemi method might relatively an unreliable method therefore.

In this study, it had clearly shown that the fiber saturation point have significant correlations with certain physical properties, extractives contents and also anatomical properties. Secondly, there is also certain significant between several pairs of properties (Table 32). Walker (1993) stated that a negative correlation exist between basic density and moisture content. The FSP determined by the four methods showed the similar correlation trend to this wood property. Higher FSP indicates that there is bulk moisture content in the timber; thus FSP is positively correlated with water permeability in wood.

Wangaard and Granados (1967) showed that the fiber saturation point had increase after the extractives had been removing by a series of neutral solvents in their study. In this study, it is obviously showed the percentage of extractive contents by using methanol as extractant was negative correlate with FSP of the four test methods; however significant negative correlation of FSP only exist in Walker method (r = -0.628) and Awoyemi-

Walker method (r = -0.625) at 0.01 level. The two regression value was closest to each other perhaps because by applying the same mathematical equation but differs by the term of basic density and oven-dry density only. Also, negative correlation exists in Walker method, Awoyemi-Walker method and Vorreiter method with cold water and hot water solubility. An unexpected result showed FSP in Awoyemi method was positive correlate to the cold water and hot water solubility; again this is evidence for the highly unreliable method of Awoyemi method. Besides, the substrate of wood as heartwood and sapwood added together complicates the effect to the wood extractive contents in the correlation analysis. According to Haygreen & Bowyer (1989b; cited, Ona *et al.*, 1997), higher basic densities within the heartwood part are positively correlated with high extractive contents at that part compare to sapwood. In this study, basic density is positively correlation but did not vary significantly to the methanol extractives, cold water solubility and hot water solubility. In future, FSP correlations with extractives should not mix data on heartwood with sapwood.

The basic density is significant negatively correlated to percentage of water permeability (moisture content) within a species (Walker, 1993). This indicated that wood showed a trend of decline wood density with increasing water permeability. Denser wood species have less void space for holding water while less dense wood species have more void space which can hold more water. As example in this study, *Shorea* sp. (Light Red Meranti) with the lowest basic density of 271.178 kg/m^3 among the 14 species were higher in water permeability of 181.60%; while *Upuna borneensis* (Penyau) with the highest basic density of 795.529 kg/m^3 were lowest in water permeability of 24.71%. Langrish and Walker (1993) stated that presence of tyloses, secreting gums and resins make the vessels in heartwood become inactive for water permeability. Extractive was found in cell wall and

cell lumen, hence higher in extractive contents will block and reduce the permeability of water into the cell wall. Thus, extractive contents in timber species was negatively correlate to water permeability in the timber species. This means higher extractives contents in wood body might also lower the absorption and desorption rate of water, hence FSP can be influenced by presence of extractives contents.

Note that since certain anatomical properties are associated with wood density, hence these properties will also correlate well with FSP. The basic density was positively correlated with fiber wall thickness (Baas & Wheeler, 2000) which in turn represent as vital indicator of wood properties including hardness, strength and dimensional stability. Denser woods have a large proportion of thick-walled fibers (Butterfield, 1993) and this revealed smaller fiber lumen diameter which might become an obstacle for water flow in and thus results in low FSP. Positive correlation coexists between vessel diameter and water permeability, a relatively small difference in vessel diameter can make a large difference in hydraulic conductivity in trees (Baas & Wheeler, 2000). The vessel diameter showed negative correlation to vessel density (Baas & Wheeler, 2000). Also, the permeability would be poor if the vessels are too small (Walker, 1993). Lower vessel density indicates that the vessel's diameter in particular wood species would be bigger; hence water or moisture conductivity in vessel was high and subsequently results in higher water permeability and FSP.

6.0 Conclusion

Four simple methods of fiber saturation point determination will yield different results depending the evaluation criteria. For example, the Awoyemi method required the rate of absorption and desorption at particular moisture content; Walker method was based on volumetric swelling and density; and Vorreiter method was based on bulk density. Comparing the 4 test methods, Vorreiter method is a more reliable estimate of the fiber saturation point; while Awoyemi method is the least reliable method due to its unusually range of FSP values and the FSP showed unexpected correlation with several wood properties.

In this study, the fiber saturation point of the four methods has their own correlation to the properties of wood. However, not all the wood properties will affect the FSP. Overall, basic density, water permeability, extractives content, fiber lumen diameter and fiber wall thickness were important determinants of FSP. These wood properties should be taken in consideration also for their influence on the final products in wood processing.

Recommendations

It is recommended that all the wood blocks subjected to fiber saturation point determination should be end coated at both ends of the cross section, and their longitudinal sections examined only because in practice wood surfaces are mainly longitudinal in nature. This is because vessels and fiber are aligned in the longitudinal direction with their opening at the cross section. Applying end coated to the cross section will control the rate of uptake or absorption of water into the timber body. Water will only penetrate into vessels or fiber at the radial or tangential direction. Since these two directions were low in penetration, hence error during experiment can be minimize and the data on gaining fiber saturation point might be more accurate. Also, FSP study to re-examine the Awoyemi method should be made in a conditioning chamber to maintain constant environment through the study.

Also, other wood properties should also taken into consideration in the relationships of fiber saturation point with these wood properties. Absorption of water might also affected by the fiber pitting at the fiber wall. Hence, the distribution and type of fiber pitting, it's variation and fiber pitting density can be studied to explore whether these properties have any correlation with fiber saturation point.

The measurement of contact angle for each wood species also should be introduced into the experiment to test the contact angle between wood with water by using Contact Angle Meter (CAM) 100 machine. This is because some of the wood species have the characteristic of water repellency to prevent water penetration into the wood body, and hence affects FSP.

lso, variation of vessels (pores) density should be further studied if the timber species has easonal growth rings present in some tropical species. This is because the pore density ould be typically more abundant at the portion of earlywood and also bigger in diameter. n contrast, the pore density at the portion of latewood was expected to be less abundant nd of smaller diameter.

is also recommend that fresh felled wood be used to test the differences of FSP between reen wood and air-dried wood. In addition, more novel methods for determination of fiber aturation point should be tried to compare the fiber saturation point between different ethods. For example, Stamm graphical method (1964; cited, Walker, 1993) and "solute xclusion technique" developed by Feist and Tarkow (1967) can be tried.

he extent of wood extractive micro distribution in the wood cell walls affecting FSP eeds to be further examined before this property could be regarded as a likely strong eterminant of FSP variations between and within wood species.

7.0 References

Alhgren, P.A., Wood, J.R. & Goring, D.A.I. (1972). The fiber saturation point of various morphological subdivisions of Douglas-fir and Aspen wood. *Wood Science and Technology, 6*, 81-84.

Anonymous (2000). Retrieved August 19, 2008, from http://timber.ce.wsu.edu/Supplements/Moisture/moisture%20page2.htm

ASTM (American Society for Testing and Materials) (2000). D1110-84 (Reapproved 1995): Standard Test Methods for Water Solubility of Wood. In Annual Book of ASTM Standards.Volume 04.10 (pp188-189). Philadelphia: ASTM.

Arevola, R. & Hernandez, R.E. (2004). Influence of moisture sorption on the tangential compression strength of Mahogany wood (*Swietenia macrophylla* King). *Wood Sci Technol, 37*(5), 419-425.

Awoyemi, L. (2006). Estimation of fiber saturation point from sorption behavior of wood in water. *Journal of The Institute of Wood Science, 17*(2), 110-113.

Baas, P. & Wheeler, E.A. (2000). Wood structure of Southeast Asian timbers-the PROSEA wood reviewed. In Kim, Y.S. (Ed.), *New Horizons in wood Anatomy* (pp. 1-9). Kwangju: Chonnam Nat'l Univ. Press.

Barkas, W.W. (1935). Fiber saturation point of wood. *Nature, 135*, 545-545.

Barkas, W.W. (1932). Retention of moisture by wood. *Nature, 130*, 699-700.

Burgert, I., Bernasconi, A., Niklas, K.J. & Eckstein, D. (2001). The influence of rays on the transverse elastic anisotropy in green woods of deciduous trees. *Holzforschung 55*, 449-454.

Butterfield, B.G. (1993). The structure of wood: an overview. In Walker, J.C.F., Butterfield, B.G., Langrish, T.A.G., Harris, J.M., & Uprichard, J.M., *Primary wood processing* (pp. 1-22). New York: Chapman & Hall.

Dinwoodie, J.M. (1981). *Timber, its nature and behavior*. New York: Van Nostrand Reinhold Co. Ltd.

Dinwoodie, J.M. (1989). *Wood: Nature's cellular, polymeric, fiber-composite*. London: The Institute of Metals.

Durbak, I., Green, D.W., Highley, T.L., Howard, J.L., McKeever, D.B., Miller, R.B., Pettersen, R.C., Rowell, R.M., Simpson, W.T., Skog, K.E., White, R.H., Winandy, J.E., Zerbe, J.I. & USDA Forest Service (1998). *Kirk-Othmer encyclopedia of chemical technology* (4th ed.). John Wiley & Sons, Inc.

Feist, W.C. & Tarkow, H. (1967). A new procedure for measuring fiber saturation points. *Forest Products Journal, 17*(10), 65-68.

Hamdan, H., Hill, C.A.S., Zaidon, A., Anwar, U.M.K. & Abd. Latif, M. (2007). Equilibrium moisture content and volumetric changes of *Giganthochloa scortechinii*. *Journal of Tropical Forest Science, 19*(1), 18-24.

Hernandez, R.E. (2007). Influence of accessory substances, wood density and interlocked grain on the compressive properties of hardwoods. *Wood Sci Technol, 41*(3), 249-265.

IAWA Committee (1989). IAWA list of microscopic features for hardwood identification. *IAWA Bulletin n.s. 10* (3), 219-332.

Jem, J.E.M. (2008). *Radial variation in wood quality of Acacia mangium Willd. wood.* Kota Samarahan: Unpublished Final-Year Project report, Department of Plant Science and Environmental Ecology, Universiti Malaysia Sarawak.

Langrish, T.A.G. & Walker, J.C.F. (1993). Transport processes in wood. In Walker, J.C.F., Butterfield, B.G., Langrish, T.A.G., Harris, J.M., & Uprichard, J.M., *Primary wood processing* (pp. 121-152). New York: Chapman & Hall.

Lihra, T., Cloutier A. & Zhang S.Y. (2000). Longitudinal and transverse permeability of balsam fir wetwood and normal heartwood. *Wood and Fiber Science, 32*(2), 164-178.

Negi, S.S. (1997). *Wood science and technology*. India: International Book Distributors.

Noguchi, M., Sugihara, H. & Matsuyoshi, R. (1965). Wood cutting with a pendulum dynamometer (v)-effect of moisture content. *Wood Research, 34*, 45-53.

Ona, T., Sonoda, T., Ito, K. & Shibata, M. (1997). Relationship between various extracted basic densities and wood chemical components in *Eucalyptus camaldulensis*. *Wood Science and Technology, 31*, 205-216.

Panshin, A.J. & de Zeeuw, C. (1980). *Textbook of wood technology* (4th ed.). United States of America: McGraw-Hill Inc.

Rees, L.W. & Buckman, S.J. (1938). Moisture movement in wood above the fiber saturation point. *Journal of agricultural research, 57*(3), 161-187.

Rowell, R.M. & Rowell, J.S. (1989). Moisture sorption properties of acetylated lignocellulosic fibers. In Schuerch, C. (Ed.), *Cellulose and wood* (pp. 343-355). New York: John Wiley & Sons, Inc.

Siau, J.F. (1995). *Wood: Influence of moisture on physical properties*. New York: Virginia Polytechnic Institute and State University.

Stone, J.E. & Scallan, A.M. (1967). The effect of component removal upon the porous structure of the cell wall of wood. (II) Swelling in water and the fiber saturation point. *Tappi, 50*(10), 496-501.

TAPPI (1988). Basic density and moisture content of pulpwood (TAPPI T258 om-85). In TAPPI Test Methods. Volume 1. United States of America: TAPPI Technology Park.

TAPPI (1988). Solvent extractives of wood and pulp (TAPPI T204 om-88). In TAPPI Test Methods. Volume 1. United States of America: TAPPI Technology Park.

TAPPI (1988). Water solubility of wood and pulp (TAPPI T264 om-88). In TAPPI Test Methods. Volume 1. United States of America: TAPPI Technology Park.

Uprichard, J.M. (1993). Wood extractives. In Walker, J.C.F., Butterfield, B.G., Langrish, T.A.G., Harris, J.M., & Uprichard, J.M., *Primary wood processing* (pp. 56-57). New York: Chapman & Hall.

Walker, J.C.F. (1993). Dimensional instability of timber. In Walker, J.C.F., Butterfield, B.G., Langrish, T.A.G., Harris, J.M., & Uprichard, J.M., *Primary wood processing* (pp. 68-94). New York: Chapman & Hall.

Walker, J.C.F. (1993). Water and wood. In Walker, J.C.F., Butterfield, B.G., Langrish, T.A.G., Harris, J.M., & Uprichard, J.M., *Primary wood processing* (pp. 68-94). New York: Chapman & Hall.

Walker, J.C.F., Butterfield, B.G., Langrish, T.A.G., Harris, J.M., & Uprichard, J.M. (1993). *Primary wood processing* (1st ed.). New York: Chapman & Hall.

Wangaard, F.F. & Granados, L.A. (1967). The effect of extractives on water-vapor sorption by wood. *Wood Science and Technology, 1*(4), 253-277.

Wikipedia (2008). *Wood drying*. Retrieved May 6, 2008, from http://en.wikipedia.org/wiki/wood drying

Wong, A.H.H. & Singh, A.P. (1997). Microbial decay in an extremely durable Malaysian hardwood Belian (*Eusideroxylon zwageri*) - an overview. *The International research Group on Wood Preservation Document* No: IRG/WP 97-10216.

Wong, A.H.H. & Singh, A.P. (2001). The high decay resistance in the sapwood of the naturally durable Malaysian hardwood Belian (*Eusideroxylon zwageri*). *The International research Group on Wood Preservation Document* No: IRG/WP 01-10410.

Wong, A.H.H., Wilkes, J. & Heather, W.A. (1983). Influence of wood Density and Extractives Content on the Decay Resistance of the Heartwood of *Eucalyptus delegatensis* R. T Baker. *Journal of the Institute of Wood Science, 9*, 261- 263.

Yamamoto, H., Sassus, F., Ninomiya, M. & Gril, J. (2001). A model of anisotropic swelling and shrinking process of wood. *Wood Science and Technology, 35*(1-2), 167-181.

Zeronian, S.H., & Mee, S.K. (1989). Studies on the water vapor sorption hysteresis of viscose rayon and of chemically modified viscose rayon. In Schuerch, C. (Ed.), *Cellulose and wood* (pp. 325-341). New York: John Wiley & Sons, Inc.

Appendices

Table 1: Fiber saturation point on different wood species at room temperature

Wood species	Fiber saturation point (%)
Ash, white	24.0
Birch, yellow	27.0
Douglas fir	26.0
Hemlock, western	28.0
Larch, western	28.0
Pine, loblolly	21.0
Pine, longleaf	25.5
Pine, red	24.0
Spruce, red	27.0
Spruce, Sitka	28.5

(Adapted from Anonymous (2000))

Table 33: Mean value of air-dry moisture contents (%) of 14 timber species

Wood species	Air-dry moisture content (%)
Upuna borneensis	9.24
Shorea macrophylla	11.51
Neolamarkia cadamba	11.99
Hevea brasiliensis	12.23
Lithocarpus sp.	12.48
Tectona grandis	12.72
Durio sp.	13.32
Shorea sp.	14.01
Fagus sylvatica	14.35
Sindora sp.	14.44
Endospermum diadenum	15.71
Hydnocarpus sp.	16.12
Dipterocarpus sp.	16.19
Acacia mangium	22.44

N = 10

Table 34: Mean value of oven-dry density (kg/m^3) of 14 timber species

Wood species	Oven-dry density (Kg/m^3)
Shorea sp.	297.007
Neolamarkia cadamba	297.951
Shorea macrophylla	331.461
Endospermum diadenum	404.238
Sindora sp.	604.671
Hevea brasiliensis	616.981
Fagus sylvatica	666.957
Tectona grandis	670.236
Acacia mangium	725.706
Durio sp.	767.811
Lithocarpus sp.	819.515
Hydnocarpus sp.	819.769
Dipterocarpus sp.	881.556
Upuna borneensis	882.357

Table 35: Comparison of methanol extractives (%) study by Jem (2008) and Low (2009)

	methanol extractives (%)	
Species	Study by Jem (2008)	Study by Low (2009)
Acacia mangium	3.0-12.5	11.25
Endospermum diadenum	2.4-2.8	2.54
Neolarmarkia cadamba	3.0-4.4	2.29
Shorea macrophylla	2.5-3.3	3.94

Table 36: Mean value of physical properties of 14 timber species

Wood species	Air-dry MC (%)	Water permeability (%)	Basic density (kg /m³)	Oven-dry density (kg/m³)	Solvent extractives (%)	Cold water solubility (%)	Hot water solubility (%)
Dipterocarpus sp.	16.19	40.60	747.158	881.556	5.4	3.0	5.6
Durio sp.	13.32	71.61	660.956	767.811	1.2	2.3	3.5
Endospermum diadenum	15.71	179.29	373.716	404.238	2.5	3.3	5.0
Hydnocarpus sp.	16.12	57.69	708.148	819.769	0.8	2.3	2.6
Lithocarpus sp.	12.48	45.05	713.623	819.515	4.5	4.3	7.0
Neolamarkia cadamba	11.99	130.69	276.959	297.951	2.3	3.3	4.6
Shorea macrophylla	11.51	95.66	309.131	331.461	3.9	3.8	5.2
Shorea sp.	14.01	181.60	271.178	297.007	3.8	3.4	5.4
Sindora sp.	14.44	100.36	542.464	604.671	3.7	4.5	8.0
Upuna borneensis	9.24	24.71	795.529	882.357	9.9	4.1	6.3
Acacia mangium	22.44	29.70	659.312	725.706	11.2	5.6	11.6
Fagus sylvatica	14.35	95.28	544.893	666.957	1.5	3.3	6.0
Hevea brasiliensis	12.23	93.60	562.479	616.981	3.3	5.4	17.4
Tectona grandis	12.72	26.22	630.935	670.236	8.4	4.7	7.0

Table 37: Mean value of anatomical properties of 14 timber species

Wood species	Vessel density (#/mm²)	Vessel diamter (μm)	Fiber length (mm)	Fiber diameter (μm)	Fiber lumen diameter (μm)	Fiber wall thickness (μm)
Dipterocarpus sp.	5.26	177.12	1.73	22.04	14.40	3.82
Durio sp.	3.10	197.36	1.68	24.64	12.64	6.00
Endospermum diadenum	4.28	200.48	2.34	46.28	32.36	6.96
Hydnocarpus sp.	14.39	91.92	3.55	44.72	16.92	13.90
Lithocarpus sp.	3.34	209.32	1.46	22.28	11.76	5.26
Neolamarkia cadamba	2.57	196.44	1.14	28.44	21.00	3.72
Shorea macrophylla	3.07	188.52	1.28	31.65	22.95	4.35
Shorea sp.	4.01	178.08	1.25	31.00	23.04	3.98
Sindora sp.	2.50	134.36	1.37	22.72	13.60	4.56
Upuna borneensis	6.21	177.68	1.46	17.12	10.48	3.32
Acacia mangium	6.98	153.15	1.19	16.15	9.55	3.30
Fagus sylvatica	126.24	47.68	1.14	18.56	9.28	4.64
Hevea brasiliensis	2.74	190.88	1.63	24.84	14.88	4.98
Tectona grandis	6.98	177.56	1.46	26.80	18.72	4.04

Table 38: Descriptive data for basic density based on timber species

Species	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
Dipterocarpus sp.	10	747.1581	4.03966	1.27745	744.2683	750.0479	741.52	754.72
Durio sp.	10	660.9562	29.72384	9.39950	639.6930	682.2194	622.42	706.61
Endospermum diadenum	10	373.7156	32.94314	10.41754	350.1495	397.2817	329.59	438.08
Hydnocarpus sp.	10	708.1484	11.23626	3.55322	700.1105	716.1863	686.89	720.25
Lithocarpus sp.	10	713.6232	28.54184	9.02572	693.2056	734.0408	649.53	736.35
Neolarmarkia cadamba	10	276.9589	4.00761	1.26732	274.0920	279.8258	271.42	283.80
Shorea macrophylla	10	309.1308	27.47155	8.68727	289.4788	328.7828	274.71	345.43
Shorea sp.	10	271.1779	11.80782	3.73396	262.7311	279.6247	255.77	290.78
Sindora sp.	10	542.4636	29.85965	9.44245	521.1033	563.8239	496.37	591.30
Upuna borneensis	10	795.5291	48.25071	15.25821	761.0126	830.0456	741.78	896.32
Acacia mangium	10	659.3123	28.24372	8.93145	639.1080	679.5166	615.96	723.35
Fagus sylvatica	10	544.8927	7.30049	2.30862	539.6702	550.1152	535.96	557.14
Hevea brasiliensis	10	562.4793	59.41942	18.79007	519.9732	604.9854	491.37	663.19
Tectona grandis	10	630.9350	39.75004	12.57007	602.4995	659.3705	570.56	694.38
Total	140	556.8915	176.78731	14.94125	527.3500	586.4330	255.77	896.32

Table 39: Descriptive data for water permeability based on timber species

Species	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
Dipterocarpus sp.	10	40.5975	1.32719	0.41969	39.6481	41.5469	38.65	42.43
Durio sp.	10	71.6096	6.58312	2.08176	66.9003	76.3189	60.67	79.83
Endospermum diadenum	10	179.2900	21.38964	6.76400	163.9888	194.5912	146.23	216.58
Hydnocarpus sp.	10	57.6891	1.54990	0.49012	56.5804	58.7978	55.06	60.24
Lithocarpus sp.	10	45.0457	14.95326	4.72864	34.3488	55.7426	26.94	62.63
Neolarmarkia cadamba	10	130.6904	30.85493	9.75719	108.6181	152.7627	94.11	175.22
Shorea macrophylla	10	95.6566	18.11745	5.72924	82.6962	108.6170	64.82	119.41
Shorea sp.	10	181.5992	44.70530	14.13706	149.6190	213.5794	101.84	249.66
Sindora sp.	10	100.3638	8.27537	2.61690	94.4440	106.2836	87.74	114.15
Upuna borneensis	10	24.7121	9.08142	2.87180	18.2156	31.2086	9.34	36.91
Acacia mangium	10	29.6970	3.29769	1.04282	27.3380	32.0560	25.80	35.14
Fagus sylvatica	10	95.2806	3.95661	1.25119	92.4502	98.1110	90.79	101.52
Hevea brasiliensis	10	93.5956	20.93276	6.61952	78.6212	108.5700	66.54	120.13
Tectona grandis	10	26.2243	10.72300	3.39091	18.5535	33.8951	10.69	39.63
Total	140	83.7180	53.45666	4.51791	74.7852	92.6507	9.34	249.66

Table 40: Descriptive data for solvent extractives based on timber species

Species	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
Dipterocarpus sp.	2	5.3643	0.28404	0.20085	2.8122	7.9163	5.16	5.57
Durio sp.	2	1.2088	0.01513	0.01070	1.0728	1.3448	1.20	1.22
Endospermum diadenum	2	2.5388	0.23674	0.16740	0.4118	4.6658	2.37	2.71
Hydnocarpus sp.	2	0.7635	0.00983	0.00695	0.6751	0.8518	0.76	0.77
Lithocarpus sp.	2	4.5087	0.07538	0.05330	3.8315	5.1859	4.46	4.56
Neolarmarkia cadamba	2	2.2861	0.05049	0.03570	1.8325	2.7397	2.25	2.32
Shorea macrophylla	2	3.9413	0.02751	0.01945	3.6941	4.1884	3.92	3.96
Shorea sp.	2	3.8083	0.07729	0.05465	3.1139	4.5026	3.75	3.86
Sindora sp.	2	3.7438	0.07403	0.05235	3.0786	4.4089	3.69	3.80
Upuna borneensis	2	9.9242	0.13287	0.09395	8.7304	11.1179	9.83	10.02
Acacia mangium	2	11.2482	0.22917	0.16205	9.1892	13.3073	11.09	11.41
Fagus sylvatica	2	1.5451	0.01640	0.01160	1.3977	1.6925	1.53	1.56
Hevea brasiliensis	2	3.2820	0.03606	0.02550	2.9580	3.6060	3.26	3.31
Tectona grandis	2	8.4209	0.06781	0.04795	7.8116	9.0301	8.37	8.47
Total	28	4.4703	3.17751	0.60049	3.2382	5.7024	0.76	11.41

Table 41: Descriptive data for cold water solubility based on timber species

Species	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
Dipterocarpus sp.	2	2.9996	0.38233	0.27035	-0.4356	6.4347	2.73	3.27
Durio sp.	2	2.2762	0.13287	0.09395	1.0824	3.4699	2.18	2.37
Endospermum diadenum	2	3.2478	0.45941	0.32485	-0.8799	7.3754	2.92	3.57
Hydnocarpus sp.	2	2.3278	0.21588	0.15265	0.3881	4.2674	2.18	2.48
Lithocarpus sp.	2	4.3329	0.01386	0.00980	4.2084	4.4574	4.32	4.34
Neolarmarkia cadamba	2	3.3409	0.02638	0.01865	3.1039	3.5778	3.32	3.36
Shorea macrophylla	2	3.7692	0.37909	0.26806	0.3632	7.1752	3.50	4.04
Shorea sp.	2	3.4310	0.13067	0.09240	2.2569	4.6051	3.34	3.52
Sindora sp.	2	4.4770	0.21319	0.15075	2.5615	6.3924	4.33	4.63
Upuna borneensis	2	4.1268	0.16589	0.11730	2.6364	5.6172	4.01	4.24
Acacia mangium	2	5.5525	0.35015	0.24759	2.4065	8.6984	5.30	5.80
Fagus sylvatica	2	3.3327	0.15268	0.10796	1.9609	4.7044	3.22	3.44
Hevea brasiliensis	2	5.3878	0.06692	0.04732	4.7865	5.9891	5.34	5.44
Tectona grandis	2	4.7261	0.30010	0.21220	2.0298	7.4224	4.51	4.94
Total	28	3.8091	1.00913	0.19071	3.4178	4.2004	2.18	5.80

Table 42: Descriptive data for hot water solubility based on timber species

Species	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
Dipterocarpus sp.	2	5.5558	0.13612	0.09625	4.3329	6.7788	5.46	5.65
Durio sp.	2	3.5278	0.09716	0.06870	2.6549	4.4007	3.46	3.60
Endospermum diadenum	2	5.0434	0.27132	0.19185	2.6057	7.4810	4.85	5.24
Hydnocarpus sp.	2	2.6293	0.16956	0.11990	1.1058	4.1528	2.51	2.75
Lithocarpus sp.	2	6.9904	0.58534	0.41390	1.7313	12.2495	6.58	7.40
Neolarmarkia cadamba	2	4.5570	0.07509	0.05310	3.8823	5.2317	4.50	4.61
Shorea macrophylla	2	5.1960	0.07898	0.05585	4.4864	5.9057	5.14	5.25
Shorea sp.	2	5.4111	0.32103	0.22700	2.5268	8.2954	5.18	5.64
Sindora sp.	2	8.0360	0.03069	0.02170	7.7603	8.3117	8.01	8.06
Upuna borneensis	2	6.3406	0.16610	0.11745	4.8482	7.8329	6.22	6.46
Acacia mangium	2	11.5944	1.07777	0.76210	1.9110	21.2778	10.83	12.36
Fagus sylvatica	2	5.9932	0.09009	0.06370	5.1838	6.8026	5.93	6.06
Hevea brasiliensis	2	17.3991	0.30215	0.21365	14.6844	20.1137	17.19	17.61
Tectona grandis	2	6.9670	0.04547	0.03215	6.5584	7.3755	6.93	7.00
Total	28	6.8029	3.66149	0.69196	5.3832	8.2227	2.51	17.61

Table 43: Descriptive data for vessel density based on timber species

Species	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
Dipterocarpus sp.	50	5.2550	0.98262	0.13896	4.9757	5.5343	3.50	9.00
Durio sp.	50	3.0950	0.78554	0.11109	2.8718	3.3182	1.50	5.00
Endospermum diadenum	50	4.2750	1.18478	0.16755	3.9383	4.6117	2.00	6.75
Hydnocarpus sp.	50	14.3900	2.23331	0.31584	13.7553	15.0247	10.00	21.50
Lithocarpus sp.	50	3.3400	1.16470	0.16471	3.0090	3.6710	1.75	6.75
Neolarmarkia cadamba	50	2.5700	0.53223	0.07527	2.4187	2.7213	1.50	3.75
Shorea macrophylla	50	3.0650	0.42502	0.06011	2.9442	3.1858	1.75	4.25
Shorea sp.	50	4.0050	1.01455	0.14348	3.7167	4.2933	2.50	7.25
Sindora sp.	50	2.4950	0.73971	0.10461	2.2848	2.7052	1.00	4.50
Upuna borneensis	50	6.2100	1.69209	0.23930	5.7291	6.6909	2.50	9.25
Acacia mangium	40	6.9813	0.97794	0.15463	6.6685	7.2940	5.25	9.75
Fagus sylvatica	50	126.2400	21.76175	3.07758	120.0554	132.4246	80.00	184.00
Hevea brasiliensis	50	2.7400	0.69429	0.09819	2.5427	2.9373	1.25	4.25
Tectona grandis	50	6.9800	1.83492	0.25950	6.4585	7.5015	4.00	12.25
Total	690	13.7859	32.14869	1.22388	11.3829	16.1889	1.00	184.00

Table 44: Descriptive data for vessel diameter based on timber species

Species	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
Dipterocarpus sp.	125	177.1200	19.26329	1.72296	173.7098	180.5302	130.00	230.00
Durio sp.	125	197.3600	20.95094	1.87391	193.6510	201.0690	155.00	300.00
Endospermum diadenum	125	200.4800	20.55112	1.83815	196.8418	204.1182	145.00	245.00
Hydnocarpus sp.	125	91.9200	16.51959	1.47756	88.9955	94.8445	60.00	135.00
Lithocarpus sp.	125	209.3200	27.01063	2.41590	204.5382	214.1018	150.00	265.00
Neolarmarkia cadamba	125	196.4400	17.14285	1.53330	193.4052	199.4748	165.00	230.00
Shorea macrophylla	125	188.5200	21.07996	1.88545	184.7882	192.2518	125.00	235.00
Shorea sp.	125	178.0800	17.72077	1.58499	174.9429	181.2171	135.00	215.00
Sindora sp.	125	134.3600	24.19657	2.16421	130.0764	138.6436	95.00	190.00
Upuna borneensis	125	177.6800	16.92660	1.51396	174.6834	180.6766	135.00	215.00
Acacia mangium	100	153.1500	16.50918	1.65092	149.8742	156.4258	120.00	185.00
Fagus sylvatica	125	47.6800	5.83869	0.52223	46.6464	48.7136	35.00	60.00
Hevea brasiliensis	125	190.8800	20.31073	1.81665	187.2843	194.4757	145.00	235.00
Tectona grandis	125	177.5600	67.97656	6.08001	165.5260	189.5940	55.00	340.00
Total	1725	165.9362	51.53566	1.24083	163.5025	168.3699	35.00	340.00

Table 45: Descriptive data for fiber length based on timber species

Species	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
Dipterocarpus sp.	125	1.7270	0.12012	0.01074	1.7057	1.7482	1.50	2.00
Durio sp.	125	1.6784	0.16261	0.01454	1.6496	1.7071	1.33	1.97
Endospermum diadenum	125	2.3435	0.21562	0.01929	2.3053	2.3817	1.85	2.81
Hydnocarpus sp.	125	3.5501	0.38123	0.03410	3.4826	3.6176	2.80	4.60
Lithocarpus sp.	125	1.4597	0.11630	0.01040	1.4391	1.4803	1.26	1.89
Neolarmarkia cadamba	125	1.1417	0.06751	0.00604	1.1297	1.1536	1.02	1.30
Shorea macrophylla	100	1.2849	0.07553	0.00755	1.2699	1.2999	1.15	1.45
Shorea sp.	125	1.2506	0.07494	0.00670	1.2374	1.2639	1.10	1.43
Sindora sp.	125	1.3693	0.08197	0.00733	1.3548	1.3838	1.19	1.57
Upuna borneensis	125	1.4608	0.11192	0.01001	1.4409	1.4806	1.22	1.85
Acacia mangium	100	1.1875	0.05735	0.00573	1.1761	1.1989	1.07	1.33
Fagus sylvatica	125	1.1380	0.08646	0.00773	1.1227	1.1533	0.98	1.35
Hevea brasiliensis	125	1.6324	0.13318	0.01191	1.6088	1.6560	1.29	1.92
Tectona grandis	125	1.4646	0.09598	0.00858	1.4476	1.4816	1.24	1.72
Total	1700	1.6319	0.63909	0.01550	1.6015	1.6623	0.98	4.60

Table 46: Descriptive data for fiber diameter based on timber species

Species	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
Dipterocarpus sp.	125	22.0400	3.54100	0.31672	21.4131	22.6669	15.00	35.00
Durio sp.	125	24.6400	5.24312	0.46896	23.7118	25.5682	15.00	40.00
Endospermum diadenum	125	46.2800	7.26525	0.64982	44.9938	47.5662	25.00	60.00
Hydnocarpus sp.	125	44.7200	7.02254	0.62812	43.4768	45.9632	30.00	70.00
Lithocarpus sp.	125	22.2800	4.33031	0.38731	21.5134	23.0466	15.00	35.00
Neolarmarkia cadamba	125	28.4400	4.03693	0.36107	27.7253	29.1547	20.00	35.00
Shorea macrophylla	100	31.6500	4.08588	0.40859	30.8393	32.4607	20.00	40.00
Shorea sp.	125	31.0000	4.01610	0.35921	30.2890	31.7110	20.00	40.00
Sindora sp.	125	22.7200	3.39021	0.30323	22.1198	23.3202	15.00	30.00
Upuna borneensis	125	17.1200	2.85849	0.25567	16.6140	17.6260	10.00	25.00
Acacia mangium	100	16.1500	2.54802	0.25480	15.6444	16.6556	10.00	20.00
Fagus sylvatica	125	18.5600	3.22640	0.28858	17.9888	19.1312	10.00	30.00
Hevea brasiliensis	125	24.8400	4.39648	0.39323	24.0617	25.6183	15.00	35.00
Tectona grandis	125	26.8000	4.81094	0.43030	25.9483	27.6517	20.00	45.00
Total	1700	27.0353	9.93528	0.24097	26.5627	27.5079	10.00	70.00

Table 47: Descriptive data for fiber lumen diameter based on timber species

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
Dipterocarpus sp.	125	14.4000	3.27503	0.29293	13.8202	14.9798	10.00	25.00
Durio sp.	125	12.6400	4.23960	0.37920	11.8895	13.3905	5.00	25.00
Endospermum diadenum	125	32.3600	6.49367	0.58081	31.2104	33.5096	15.00	45.00
Hydnocarpus sp.	125	16.9200	5.88135	0.52604	15.8788	17.9612	5.00	35.00
Lithocarpus sp.	125	11.7600	3.87590	0.34667	11.0738	12.4462	5.00	20.00
Neolarmarkia cadamba	125	21.0000	3.59211	0.32129	20.3641	21.6359	15.00	30.00
Shorea macrophylla	100	22.9500	4.21008	0.42101	22.1146	23.7854	15.00	35.00
Shorea sp.	125	23.0400	3.75113	0.33551	22.3759	23.7041	10.00	30.00
Sindora sp.	125	13.6000	3.45478	0.30900	12.9884	14.2116	5.00	20.00
Upuna borneensis	125	10.4800	2.49386	0.22306	10.0385	10.9215	5.00	15.00
Acacia mangium	100	9.5500	2.02198	0.20220	9.1488	9.9512	5.00	15.00
Fagus sylvatica	125	9.2800	3.28142	0.29350	8.6991	9.8609	5.00	20.00
Hevea brasiliensis	125	14.8800	3.78153	0.33823	14.2105	15.5495	5.00	25.00
Tectona grandis	125	18.7200	3.96069	0.35426	18.0188	19.4212	10.00	30.00
Total	1700	16.5500	7.45166	0.18073	16.1955	16.9045	5.00	45.00

Table 48: Descriptive data for fiber wall thickness based on timber species

Species	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
Dipterocarpus sp.	125	3.8200	1.25306	0.11208	3.5982	4.0418	2.50	5.00
Durio sp.	125	6.0000	1.55543	0.13912	5.7246	6.2754	2.50	10.00
Endospermum diadenum	125	6.9600	1.66753	0.14915	6.6648	7.2552	2.50	12.50
Hydnocarpus sp.	125	13.9000	2.62586	0.23486	13.4351	14.3649	5.00	20.00
Lithocarpus sp.	125	5.2600	1.76274	0.15766	4.9479	5.5721	2.50	12.50
Neolarmarkia cadamba	125	3.7200	1.33259	0.11919	3.4841	3.9559	2.50	7.50
Shorea macrophylla	100	4.3500	1.35866	0.13587	4.0804	4.6196	2.50	7.50
Shorea sp.	125	3.9800	1.27381	0.11393	3.7545	4.2055	2.50	7.50
Sindora sp.	125	4.5600	1.05609	0.09446	4.3730	4.7470	2.50	7.50
Upuna borneensis	125	3.3200	1.17844	0.10540	3.1114	3.5286	2.50	5.00
Acacia mangium	100	3.3000	1.22474	0.12247	3.0570	3.5430	2.50	7.50
Fagus sylvatica	125	4.6400	1.44468	0.12922	4.3842	4.8958	2.50	7.50
Hevea brasiliensis	125	4.9800	1.57142	0.14055	4.7018	5.2582	2.50	10.00
Tectona grandis	125	4.0400	1.37606	0.12308	3.7964	4.2836	2.50	7.50
Total	1700	5.2426	3.04045	0.07374	5.0980	5.3873	2.50	20.00

Table 49: Descriptive data of correlation between FSP with physical properties, extractive contents and anatomical properties

	Mean	Std. Deviation	N
Awoyemi method	35.7821	12.91239	14
Walker Method	20.1566	6.78337	14
Awoyemi-Walker method	22.7642	8.10074	14
Vorreiter method	28.0196	8.55334	14
Basic density	556.89150	180.322485	14
Water permeability	83.7180	52.22479	14
Methanol extractives	4.4700	3.23595	14
Cold water solubility	3.8100	1.01111	14
Hot water solubility	6.8036	3.72105	14
Vessel density	13.6887	32.54431	14
Vessel diameter	165.7536	45.82086	14
Fiber length	1.6206	.63843	14
Fiber diameter	26.9457	9.14589	14
Fiber lumen diameter	16.5414	6.50874	14
Fiber wall thickness	5.2021	2.70325	14

Table 50: Descriptive data for FSP based on timber species and method used

Method	Species	Mean	Std. Deviation	N
Awoyemi method	*Dipterocarpus* sp.	21.0560	0.74167	5
	Upuna borneensis	17.4820	1.18531	5
	Acacia mangium	27.6760	4.09187	5
	Fagus sylvatica	54.8960	1.72900	5
	Hevea brasiliensis	74.6040	17.17942	5
	Tectona grandis	27.1520	4.10529	5
	Durio sp.	36.2160	2.25655	5
	Endospermum diadenum	79.1000	14.32480	5
	Hydnocarpus sp.	32.9880	5.26883	5
	Lithocarpus sp.	27.0180	4.57043	5
	Neolarmarkia cadamba	40.1160	9.80192	5
	Shorea macrophylla	50.1720	4.87342	5
	Shorea sp.	40.6820	7.12904	5
	Sindora sp.	48.5820	10.01269	5
	Total	41.2671	19.42839	70
Walker method	*Dipterocarpus* sp.	20.4050	0.67729	10
	Upuna borneensis	12.5090	4.67933	10
	Acacia mangium	13.8710	5.71498	10
	Fagus sylvatica	33.5070	3.20442	10
	Hevea brasiliensis	15.6580	1.69643	10
	Tectona grandis	9.2320	2.46877	10
	Durio sp.	20.9890	1.36120	10
	Endospermum diadenum	20.2970	2.56577	10
	Hydnocarpus sp.	19.0640	5.20237	10
	Lithocarpus sp.	18.1340	1.83817	10

	Neolarmarkia cadamba	25.3940	4.41714	10
	Shorea macrophylla	22.0220	2.70102	10
	Shorea sp.	32.1550	5.73084	10
	Sindora sp.	18.9560	1.59373	10
	Total	20.1566	7.37474	140
Awoyemi-walker method	*Dipterocarpus* sp.	24.0790	0.93220	10
	Upuna borneensis	14.0600	5.45607	10
	Acacia mangium	15.5110	7.23877	10
	Fagus sylvatica	41.0870	4.70630	10
	Hevea brasiliensis	17.1760	1.96434	10
	Tectona grandis	9.8460	2.81588	10
	Durio sp.	24.3890	1.85742	10
	Endospermum diadenum	21.9690	2.92731	10
	Hydnocarpus sp.	22.2880	6.57564	10
	Lithocarpus sp.	20.8480	2.33539	10
	Neolarmarkia cadamba	27.3750	5.18908	10
	Shorea macrophylla	23.6230	2.97048	10
	Shorea sp.	35.3080	6.78606	10
	Sindora sp.	21.1400	1.93802	10
	Total	22.7642	8.85538	140
Vorreiter method	*Dipterocarpus* sp.	20.3520	0.09531	10
	Upuna borneensis	20.2340	0.58981	10
	Acacia mangium	23.0950	0.78258	10
	Fagus sylvatica	24.6230	0.59822	10
	Hevea brasiliensis	26.5510	2.34307	10
	Tectona grandis	24.5540	1.38094	10
	Durio sp.	22.1530	0.91548	10
	Endospermum diadenum	35.9780	2.05406	10
	Hydnocarpus sp.	21.0230	0.62009	10
	Lithocarpus sp.	21.2330	0.66700	10
	Neolarmarkia cadamba	43.3200	0.62030	10
	Shorea macrophylla	40.6420	2.39151	10
	Shorea sp.	41.9290	1.07065	10
	Sindora sp.	26.5880	1.21314	10
	Total	28.0196	8.36262	140